Space Weather

European Space Weather and Space Climate Association
Space Weather and Space Climate A Timeline **Book**
https://www.edp-open.org/images/stories/books/fulldl/9782759836109-SpaceWeather_ebook.pdf
https://www.edp-open.org/books/edp-open-books/453-space-weather-and-space-climate-a-timeline
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КОСМИЧЕСКАЯ ПОГОДА СЕГОДНЯ И ВОЗМОЖНЫЕ ЭФФЕКТЫ
http://space-weather.ru/#/
Russian Heliogeophysical Monitoring Center
(http://space-weather. ru/index.php?page=home-en)

ICAO International Civil Aviation Organization

NOAA Space Weather Scales
https://www.swpc.noaa.gov/noaa-scales-explanation

Space Weather Live
https://www.spaceweatherlive.com/en.html

Community Coordinated Modeling Center
https://ccmc.gsfc.nasa.gov

DONKI Catalog - **Space Weather Database Of Notifications, Knowledge, Information**
https://kauai.ccmc.gsfc.nasa.gov/DONKI/
https://kauai.ccmc.gsfc.nasa.gov/DONKI/**https://ccmc.gsfc.nasa.gov/tools/DONKI/**

The SWx TREC Space Weather Data Portal
https://lasp.colorado.edu/space-weather-portal/home

The International Space Weather Initiative (ISWI) Workshop on Space Weather,
2 - 3 November 2021
https://www.unoosa.org/oosa/en/ourwork/psa/schedule/2021/2021-iswi-workshop.html
Presentations
https://www.unoosa.org/oosa/en/ourwork/psa/schedule/2021/2021-iswi-workshop-2021-**presentations**.html

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Journal of Space Weather and Space ClimateVolume 11 (2021)
https://www.swsc-journal.org/articles/swsc/abs/2021/01/contents/contents.html
Several **Topical Issues**

Frontiers in Astronomy and Space Sciences, THE RESEARCH TOPIC, 2021

Space Weather Prediction: Challenges and Prospects

https://www.frontiersin.org/research-topics/14044/space-weather-prediction-challenges-and-prospects#articles

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Space Weather Database Of Notifications, Knowledge, Information (DONKI)

One-stop on-line **tool for space weather** researchers and forecasters.

https://ccmc.gsfc.nasa.gov/donki/

The GOES, PAMELA and STEREO data are available at
https://www.ngdc.noaa.gov/stp/satellite/goes/
https://www.ssdc.asi.it/pamela/ and
http://www.srl.caltech.edu/STEREO/, respectively.

Earth-affecting Solar Transients: A Review of Progresses in Solar Cycle 24

Jie **Zhang**, Manuela Temmer, Nat Gopalswamy, +

https://arxiv.org/ftp/arxiv/papers/2012/2012.06116.pdf **File 2021**

2020 https://arxiv.org/abs/2012.06116

Table 1-1. Four types of Earth-affecting solar transients and their key physical processes and geoeffectiveness

Earth-affecting Solar Transients	Key Physical Processes	Effects on Near-Earth Space Environment	Effects on Technological System and Life
Solar Flares	Magnetic reconnection; Particle acceleration; Plasma heating	Disturbances in the ionosphere; Heating and expansion of upper atmosphere	High frequency radio communication; Satellite drag (Earth climate from long term variation of solar irradiance)
CMEs and ICMEs	Ideal MHD instability; Flux rope formation; Shock formation; Particle acceleration; aerodynamic drag; CME-CME interaction; Magnetic reconnection	Geomagnetic storms; Substorms; Disturbances in the ionosphere; Ionosphere scintillations; Radiation belt storms;	GPS systems and navigation; Satellite communication; High frequency radio communication; Electric power transmission; Satellite degradation and failure (Single event upset; Dielectric material charging and discharging; Surface charging); Radiation hazards to astronauts; Radiation hazards to aircraft crew and passengers
SEPs	Particle acceleration; Injection; Propagation; Turbulence	Particle Radiation Storms	Satellite degradation and failure; High frequency radio communication; Radiation hazards to astronauts; Atmospheric chemistry
SIRs/CIRs	Stream interaction; Particle acceleration	Substorms; Geomagnetic storms	Similar to CMEs to a lesser extent

SCOSTEP's next 5-year program **PRESTO** (Predictability of variable solar-terrestrial coupling) is defined to be 2020-2024
http://www.issibj.ac.cn/Publications/Forum_Reports/201404/W020190620592906717714.pdf

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Front. Astron. Space Sci., September **2020**
THE RESEARCH TOPIC **Machine Learning in Heliophysics**
https://www.frontiersin.org/research-topics/10384#articles

Лекции:
Б.Шустов "**Космические угрозы и ресурсы**"
https://www.youtube.com/playlist?list=PLmgwC9JZdQnt3j2o1akzrjmryB-F1zhtB
В.Д.Кузнецов "**Активное Солнце и его воздействие на Землю**"
https://www.youtube.com/watch?v=Jh-WnTCZPlg&list=PLmgwC9JZdQnt3j2o1akzrjmryB-F1zhtB&index=9&t=0s

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The theme issue '**Solar eruptions and their space weather impact**'. **Reviews**
Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences
v. 377 Issue 2148 **2019**
https://royalsocietypublishing.org/toc/rsta/377/2148

Extreme Events in Geospace
Origins, Predictability, and Consequences **Book**
Editor: Natalia **Buzulukova**, Elsevier, **2018**, 798 p. **File**
Site https://www.sciencedirect.com/science/article/pii/B9780128127001099921
Download PDF --> Download full book
https://www.sciencedirect.com/science/article/pii/B9780128127001099921?via%3Dihub

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Real-time Forecasting Methods Validation: SEP Scoreboard Planning Page https://ccmc.gsfc.nasa.gov/challenges/sep.php

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Publications of the Athens Neutron Monitor Group
http://cosray.phys.uoa.gr/index.php/publications-menu/publications

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Howard J Singer- **NOAA Space Weather Prediction Center**
Antti Pulkkinen – **Community Coordinated Modeling Center** (CCMC)
Terry Onsager – **NOAA space Weather Prediction Center**

OECD/IFP Futures Project on "Future Global Shocks"
"Geomagnetic Storms"
CENTRA Technology, Inc., on behalf of Office of Risk Management and Analysis, United States Department of Homeland Security
2011

http://www.oecd.org/gov/risk/46891645.pdf
The present paper considers prospects for a future global shock caused by an extreme geomagnetic storm and its effect on critical infrastructure for electrical power and satellite-enabled communications, navigation, and monitoring. Following a brief review of the phenomenon and selected risk assessment examples, the paper describes a ―worst reasonable case‖ scenario, potential consequences, and the current state of efforts to mitigate vulnerabilities and consequences. Many such efforts are operational measures relying on adequate warning. In addition to operational and infrastructure hardening measures, mitigation opportunities exist in the form of international cooperation to address critical ―bottlenecks‖ in the replacement of extra high-voltage transformers.

Extreme Events in Geospace
Origins, Predictability, and Consequences
Natalia **Buzulukova** (Ed.)
Book • **2018**
https://www.sciencedirect.com/book/9780128127001/extreme-events-in-geospace

NOAA SPACE WEATHER SCALES

https://www.swpc.noaa.gov/noaa-scales-explanation

See: SPACE WEATHER ENTERPRISE FORUM
JULY 25, 2018 Capitol Hill in Washington
https://www.ofcm.gov/meetings/swef/swefmeeting.htm

В частности,
2017 Presentations
https://www.ofcm.gov/meetings/swef/2017/2017presentations.htm

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Journal of Space Weather and Space Climate:
Topical issue: **Flares, coronal mass ejections and solar energetic particles and their space weather impacts.**
J. Space Weather Space Clim. Volume 8, **2018**
https://www.swsc-journal.org/component/list/?task=topic

- Developing New Space Weather Tools: Transitioning fundamental science to operational prediction systems
- Flares, coronal mass ejections and solar energetic particles and their space weather impacts
- Space weather effects on GNSS and their mitigation
- Measurement, Specification and Forecasting of the Solar Energetic Particle Environment and GLEs
- Brightness Variations of the Sun and Sun-like Stars and Resulting Influences on their Environments
- Scientific Challenges in Thermosphere-Ionosphere Forecasting
- Statistical Challenges in Solar Information Processing
- Satellite mission concepts developed at the Alpbach 2013 Summer School on space weather
- Solar variability, solar forcing, and coupling mechanisms in the terrestrial atmosphere
- Space Weather and Challenges for Modern Society
- COST Action ES0803
- EU-FP7 funded space weather projects

- [Space Climate]

Reprise of "Space Weather" 2001 Monograph
Comparison papers
Spase Weather Quarterly Vol. 15, Issue 1, **2018**
https://agupubs.onlinelibrary.wiley.com/hub/journal/15427390/reprise-of-space-weather-2001-monograph

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Space Weather Workshops
http://www.swpc.noaa.gov/content/prior-workshops

Journal of Space Weather and Space Climate
https://www.swsc-journal.org/component/issues/?task=all&Itemid=121

В Volume **7 (2017)** есть подборки статей под рубриками:

- Flares, coronal mass ejections and solar energetic particles and their space weather impacts.

- Developing New Space Weather Tools: Transitioning fundamental science to operational prediction systems.

- Measurement, Specification and Forecasting of the Solar Energetic Particle Environment and GLEs

- Space weather effects on GNSS and their mitigation

Space Sci. Rev. Volume 212, Issue 3–4 **2017** **Topical Collection**
The Scientific Foundation of Space Weather
https://link.springer.com/journal/11214/212/3/page/1

This link will take you **Books**
to a webpage where many book reviews are listed, all
related to **radio astronomy including space weather and solar radio**
<http://www.reeve.com/RadioScience/Radio%20Astronomy%20Publications/Radio_Astronomy_Book_Reviews.htm>

An Introduction to Space Weather
M. **Moldwin**
2008, (current printing **2013**)

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Changes of space weather and space climate at Earth orbit: An update

H.S. **Ahluwalia**

Advances in Space Research Volume 64, Issue 5, 1 September **2019**, Pages 1093-1099

https://sci-hub.se/10.1016/j.asr.2019.05.046

We present an update of the changes in space weather/space climate at Earth orbit using sunspot number (SSN) timeline (1700–2018), geomagnetic indices aa/Ap, solar polar magnetic field, interplanetary magnetic field (IMF) and galactic cosmic ray (GCR) flux in the stratosphere at high latitudes. The Cycle 24 is close to solar minimum, expected in 2020. The baseline of aa index increases monotonically from 1900 to 1986 and declines steeply afterwards, solar polar magnetic field decreases systematically for the last three cycles (22–24) as do SSNs at cycle peaks. Livingston and Penn (2009) note a long term weakening of maximum magnetic field in sunspots since 1992. They expect SSNs for the Cycle 25 to peak at 7 (a steep decline in solar activity) leading to Maunder-like minimum, in contrast to prediction of several colleagues of a Dalton minimum. The North-South asymmetry in solar polar field is pronounced for the decay phase of cycles 23, 24, itseems to change sign after the Cycle 21. GCR flux in the stratosphere is greater that in 1965 and increasing, pointing to an enhanced radiation exposure in future for the passengers on transpolar flights, the astronauts on the space station as well as those travelling to and staying on the Moon and the Mars on prolonged missions; the assets in space would have to be hardened for safety from increased radiation. We speculate about the connection between the Earth climate and changes in solar activity, inferring that the science of the Earth climate change is not settled yet.

Solar Activity from 2006 to 2014 and Short-term Forecasts of Solar Proton Events Using the ESPERTA Model

T. **Alberti**1, M. Laurenza2, E. W. Cliver3, M. Storini2, G. Consolini2, and F. Lepreti

2017 ApJ 838 59 **File**

http://sci-hub.cc/10.3847/1538-4357/aa5cb8

http://iopscience.iop.org/article/10.3847/1538-4357/aa5cb8/pdf

To evaluate the solar energetic proton (SEP) forecast model of Laurenza et al., here termed ESPERTA, we computed the input parameters (soft X-ray (SXR) fluence and ~1 MHz radio fluence) for all ≥M2 SXR flares from 2006 to 2014. This database is outside the 1995–2005 interval on which ESPERTA was developed. To assess the difference in the general level of activity between these two intervals, we compared the occurrence frequencies of SXR flares and SEP events for the first six years of cycles 23 (1996 September–2002 September) and 24 (2008 December–2014 December). We found a reduction of SXR flares and SEP events of 40% and 46%, respectively, in the latter period. Moreover, the numbers of ≥M2 flares with high values of SXR and ~1 MHz fluences (>0.1 J m−2 and >6 × 105 sfu × minute, respectively) are both reduced by ~30%. A somewhat larger percentage decrease of these two parameters (~40% versus ~30%) is obtained for the 2006–2014 interval in comparison with 1995–2005. Despite these differences, ESPERTA performance was comparable for the two intervals. For the 2006–2014 interval, ESPERTA had a probability of detection (POD) of 59% (19/32) and a false alarm rate (FAR) of 30% (8/27), versus a POD = 63% (47/75) and an FAR = 42% (34/81) for the original 1995–2005 data set. In addition, for the 2006–2014 interval the median (average) warning time was estimated to be ~2 hr (~7 hr), versus ~6 hr (~9 hr), for the 1995–2005 data set. **6 Dec 2006, 13 Dec 2006, 8 Mar 2011, 7 Aug 2011, 9 Aug 2011, 23-26 Sep 2011, 28 Jan 2012, 7-8 Mar 2012, 13 Mar 2012, 7 Jul 2012, 12 Jul 2012, 11 Apr 2013, 22-23 May 2013, 22-24 Jun 2013, 6-8 Jan 2014, 25-28 Feb 2014, 18-19 Apr 2014, 11-12 Sep 2014**

Table 1 SEP Flare List (2006–2014)

Хорошее Введение

Investigation of the Relation between Space-Weather Parameters and Forbush Decreases Automatically Selected from Moscow and Apatity Cosmic Ray Stations during Solar Cycle 23

Jibrin A. **Alhassan**, Ogbonnaya Okike, Augustine E. Chukwude

Research in Astronomy and Astrophysics (RAA) **2021**

https://arxiv.org/pdf/2108.09371.pdf

We present the results of an investigation of the relation between space-weather parameters and cosmic ray (CR) intensity modulation using algorithm-selected Forbush decreases (FDs) from Moscow (MOSC) and Apatity (APTY) neutron monitor (NM) stations during solar cycle 23. Our FD location program detected 408 and 383 FDs from

MOSC and APTY NM stations respectively. A coincident computer code employed in this work, detected 229 FDs that were observed at the same universal Time (UT) at the two stations. Out of the 229 simultaneous FDs, we formed a subset of 139 large FDs(\%) ≤−4 at Moscow station. We peformed a two dimensional regression analysis between the FD magnitudes and the space-weather data on the two samples. We find that there were significant space-weather disturbances at the time of the CR flux depressions. The correlation between the space-weather parameters and galactic cosmic ray (GCR) intensity decreases at the two NM stations are statistically significant. The implications of the present space-weather data on cosmic ray (CR) intensity depressions are highlighted.
Table 1: Selected FDs at MOSC and APTY Stations from 1996-2005

HAWC as a Ground-Based Space-Weather Observatory

C. **Alvarez**, J. R. Angeles Camacho, […] , C. de León
Solar Physics volume 296, Article number: 89 (**2021**)
https://link.springer.com/content/pdf/10.1007/s11207-021-01827-z.pdf
https://doi.org/10.1007/s11207-021-01827-z
The High Altitude Water Cherenkov (HAWC) gamma-ray observatory is located close to the equator (latitude 18∘18∘ N), at an altitude of 4100 m above sea level. HAWC has 295 water Cherenkov detectors (WCD), each containing four photomultiplier tubes (PMT). The main purpose of HAWC is the determination of the energy and arrival direction of very high energy gamma rays produced by energetic processes in the universe, HAWC also has a scaler system which counts the arrival of secondary particles to the detector. In this work we show that the scaler system of HAWC is an ideal instrument for solar modulation and space-weather studies due to its large area and high sensitivity. In order to prepare the scaler system for low energy heliospheric studies, we model and correct the efficiency variation of each PMT of the array, which result in a capability to measure variations >0.01% with high accuracy. Using the singular value decomposition method, we correct the rate deviations of all PMTs of the array, due to changes in efficiency, gain and operational voltage. We isolate and remove the atmospheric modulations of the PMTs count rates measured by the TDC-scaler data acquisition system. In particular, the atmospheric pressure at the HAWC site exhibits an oscillating behavior with a period of ∼12 hours and we make use of this periodic property to estimate the pressure coefficients for the HAWC TDC-scaler system. These corrections performed on the TDC-scaler system make the HAWC TDC-scaler system an ideal instrument for solar modulation and space-weather studies. As examples of this capability, we present the preliminary analysis of the solar modulation of cosmic rays at three time scales observed by HAWC, with an unprecedented accuracy.

Multi instrument Investigation of the impact of the Space Weather events of 6–10 September 2017

Paul O. **Amaechi**,Andrew O. Akala,Johnson O. Oyedokun,K. G Simi,O. Aghogho,Elijah O. Oyeyemi
Space Weather e2021SW002806 **2021**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021SW002806
https://doi.org/10.1029/2021SW002806
We analyzed the space weather events of **6–10 September 2017** using the multi instrument approach. We focused on the four X-class flares which emanated from the Active Region AR 12673 and the Ground Induced Currents (GICs) hazard associated with the geomagnetic storm of 7–8 September 2017. The flare effect on the equatorial electrojet (EEJ) recorded on board the SWARM satellite and on the horizontal component of the geomagnetic field (H) records of ground-based magnetometers was further examined. During the X2.2/X1.3 flares of 6/7 September, the maximum percentage GNSS vertical Total Electron Content (VTEC) increase was 6.9%/5.0% in Dakar/Porto Velho. During the X9.3/X8.2 flare of 6/10 September it was 7.9%/18.8% in Ascension Island/Kourou. The strongest Solar Flare Effect (SFE) occurred in Mbour and Kourou during the respective flare. However, the highest EEJ increase was observed during the X2.2 and X9.3 flares. Interestingly, the X.9.3 flare resulted in a stronger ionospheric response than the X8.2 flare. Furthermore, global TEC map showed a higher response in the African and South American longitude during the respective event. The total radio fade-out lasted from 30–90 mins at the Hermanus and Sao Luis ionosondes during the flares, while the risk level to critical ground infrastructures based on the geomagnetically induced currents hazard was very low risk. Our results highlight the potential GPS positioning errors induced by sudden increase in TEC and the loss of HF communication and GNSS navigation signals associated with these solar events.

Visualizing and Interpreting Unsupervised Solar Wind Classifications **Review**

Jorge **Amaya***, Romain Dupuis, Maria Elena Innocenti and Giovanni Lapenta
Front. Astron. Space Sci., 25 September **2020** |
https://doi.org/10.3389/fspas.2020.553207
https://www.frontiersin.org/articles/10.3389/fspas.2020.553207/full
One of the goals of machine learning is to eliminate tedious and arduous repetitive work. The manual and semi-automatic classification of millions of hours of solar wind data from multiple missions can be

replaced by automatic algorithms that can discover, in mountains of multi-dimensional data, the real differences in the solar wind properties. In this paper we present how unsupervised clustering techniques can be used to segregate different types of solar wind. We propose the use of advanced data reduction methods to pre-process the data, and we introduce the use of Self-Organizing Maps to visualize and interpret 14 years of ACE data. Finally, we show how these techniques can potentially be used to uncover hidden information, and how they compare with previous empirical categorizations.

Artificial intelligence unfolding for space radiation monitor data

S. **Aminalragia-Giamini**, C. Papadimitriou, I. Sandberg, A. Tsigkanos, P. Jiggens, H. Evans, D. Rodgers and I. A. Daglis
J. Space Weather Space Clim. **2018**, 8, A50
https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc180034.pdf
The reliable and accurate calculation of incident particle radiation fluxes from space radiation monitor measurements, i.e. count-rates, is of great interest and importance. Radiation monitors are relatively simple and easy to implement instruments found on board multiple spacecrafts and can thus provide information about the radiation environment in various regions of space ranging from Low Earth orbit to missions in Lagrangian points and even interplanetary missions. However, the unfolding of fluxes from monitor count-rates, being an ill-posed inverse problem, is not trivial and prone to serious errors due to the inherent difficulties present in such problems. In this work we present a novel unfolding method which uses tools from the fields of Artificial Intelligence and Machine Learning to achieve good unfolding of monitor measurements. The unfolding method combines a Case Based Reasoning approach with a Genetic Algorithm, which are both widely used. We benchmark the method on data from European Space Agency's (ESA) Standard Radiation Environment Monitor (SREM) on board the INTEGRAL mission by calculating proton fluxes during Solar Energetic Particle Events and electron fluxes from measurements within the outer Radiation Belt. Extensive evaluation studies are made by comparing the unfolded proton fluxes with data from the SEPEM Reference Dataset v2.0 and the unfolded electron fluxes with data from the Van Allen Probes mission instruments Magnetic Electron Ion Spectrometer (MagEIS) and Relativistic Electron Proton Telescope (REPT).

The virtual enhancements − solar proton event radiation (VESPER) model

Sigiava **Aminalragia-Giamini**1,2*, Ingmar Sandberg1,2, Constantinos Papadimitriou1,2,Ioannis A. Daglis1,3 and Piers Jiggens
J. Space Weather Space Clim. **2018**, 8, A06
https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc170059.pdf
A new probabilistic model introducing a novel paradigm for the modelling of the solar proton environment at 1 AU is presented. The virtual enhancements − solar proton event radiation model (VESPER) uses the European space agency's solar energetic particle environment modelling (SEPEM) Reference Dataset and produces virtual time-series of proton differential fluxes. In this regard it fundamentally diverges from the approach of existing SPE models that are based on probabilistic descriptions of SPE macroscopic characteristics such as peak flux and cumulative fluence. It is shown that VESPER reproduces well the dataset characteristics it uses, and further comparisons with existing models are made with respect to their results. The production of time-series as the main output of the model opens a straightforward way for the calculation of solar proton radiation effects in terms of time-series and the pairing with effects caused by trapped radiation and galactic cosmic rays. **11-14 Jul 1982, 27-Nov-1989 to 05-Dec-1989**

Development of research capacities in space weather: a successful international cooperation

Christine **Amory-Mazaudier**1,2*, Sandro Radicella2, Patricia Doherty3, Sharafat Gadimova4, Rolland Fleury5, Bruno Nava2, Emran Anas6, Monique Petitdidier7, Yenca Migoya-Orué2, Katy Alazo-Cuartas2 and Kazuo Shiokawa8
J. Space Weather Space Clim. **2021**, 11, 28
https://www.swsc-journal.org/articles/swsc/pdf/2021/01/swsc200097.pdf
https://doi.org/10.1051/swsc/2021006
This paper presents an international cooperation which has successfully developed research capacities in the scientific disciplines of sun–earth relations and space weather in many countries over the world during the past decades. This success was based on the deployment of scientific instruments in countries that did not have them, on the sharing of knowledge and research tools, on thesis supervision and on the integration of researchers trained in their country. This article will only focus on aspects of training conducted by ICTP, Boston College, ICG, SCOSTEP and GIRGEA. We will highlight what has been enhanced in international cooperation to achieve this success and what remains to be done.

Solar energetic particles in the inner heliosphere: status and open questions **Review**

Anastasios **Anastasiadis**, David Lario, Athanasios Papaioannou, Athanasios Kouloumvakos and Angelos Vourlidas

Philosophical Transactions of the Royal Society A v. 377 Issue 2148 Article ID: 20180100 **2019 File**

https://royalsocietypublishing.org/doi/pdf/10.1098/rsta.2018.0100

Solar energetic particle (SEP) events are related to both solar flares and coronal mass ejections (CMEs) and they present energy spectra that span from a few keV up to several GeV. A wealth of observations from widely distributed spacecraft have revealed that SEPs fill very broad regions of the heliosphere, often all around the Sun. High-energy SEPs can sometimes be energetic enough to penetrate all the way down to the surface of the Earth and thus be recorded on the ground as ground level enhancements (GLEs). The conditions of the radiation environment are currently unpredictable due to an as-yet incomplete understanding of solar eruptions and their corresponding relation to SEP events. This is because the complex nature and the interplay of the injection, acceleration and transport processes undergone by the SEPs in the solar corona and the interplanetary space prevent us from establishing an accurate understanding (based on observations and modelling). In this work, we review the current status of knowledge on SEPs, focusing on GLEs and multi-spacecraft events. We extensively discuss the forecasting and nowcasting efforts of SEPs, dividing these into three categories. Finally, we report on the current open questions and the possible direction of future research efforts. . **Хороший справочник литературы**

2. Solar energetic particle events short- and long-term forecasting

(a) Empirical or semi-empirical (b) Physics based (c) Other

Predicting Flares and Solar Energetic Particle Events: The FORSPEF Tool

A. **Anastasiadis,** A. Papaioannou, I. Sandberg, M. Georgoulis, K. Tziotziou, A. Kouloumvakos, P. Jiggens

Solar Physics September **2017**, 292:134

https://link.springer.com/content/pdf/10.1007%2Fs11207-017-1163-7.pdf

A novel integrated prediction system for solar flares (SFs) and solar energetic particle (SEP) events is presented here. The tool called forecasting solar particle events and flares (FORSPEF) provides forecasts of solar eruptive events, such as SFs with a projection to occurrence and velocity of coronal mass ejections (CMEs), and the likelihood of occurrence of an SEP event. In addition, the tool provides nowcasting of SEP events based on actual SF and CME near real-time data, as well as the SEP characteristics (e.g. peak flux, fluence, rise time, and duration) per parent solar event. The prediction of SFs relies on the effective connected magnetic field strength (BeffBeff) metric, which is based on an assessment of potentially flaring active-region (AR) magnetic configurations, and it uses a sophisticated statistical analysis of a large number of AR magnetograms. For the prediction of SEP events, new statistical methods have been developed for the likelihood of the SEP occurrence and the expected SEP characteristics. The prediction window in the forecasting scheme is 24 hours with a refresh rate of 3 hours, while the respective prediction time for the nowcasting scheme depends on the availability of the near real-time data and ranges between 15 – 20 minutes for solar flares and 6 hours for CMEs. We present the modules of the FORSPEF system, their interconnection, and the operational setup. Finally, we demonstrate the validation of the modules of the FORSPEF tool using categorical scores constructed on archived data, and we also discuss independent case studies. **26 Oct-Nov 2003, 20 Jan 2005, 7 March 2012, 2014-12-18**

http://tromos.space.noa.gr/forspef/

CESRA Highlight #1551, Oct 2017 http://www.astro.gla.ac.uk/users/eduard/cesra/?p=1551

Detection of VLF Attenuation in the Earth-Ionosphere Waveguide Caused by X-Class Solar Flares Using aGlobal Lightning Location Network

T. S. Anderson , M. P. McCarthy , R. H. Holzworth

Space Weather **Volume18, Issue3** March **2020** e2019SW002408

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019SW002408

Solar flares, energetic particles, and Earth-impacting coronal mass ejections enhance ionization in the lower ionosphere, inhibiting radio wave propagation in the Earth-ionosphere waveguide (EIWG). This enhanced ionization is observed locally by ionosondes and GPS/GNSS receivers, but spatial coverage of these observations is limited by receiver location. Very low frequency (VLF) propagation studies have previously been performed to assess the impact of space weather on the EIWG; however, these studies are typically limited by small numbers of fixed VLF transmitters and receivers and observe only the region of the EIWG along propagation paths between transmitters and receivers. Here, we use global lightning as a VLF source and an existing lightning detection network as a receiver. By mapping sferic propagation paths between lightning strokes and numerous network stations and considering how this distribution of paths changes during solar events, we can identify attenuation regions in the EIWG caused by space weather. We describe the VLF response in the EIWG to two X-class solar flares and compare mapped attenuation regions with those provided by the NOAA D-Region Absorption Prediction model. The identified attenuation regions associated with these flares match the D-Region Absorption Prediction-predicted regions well in both spatial extent and onset timing. Measurements of VLF attenuation caused by solar flares can provide ground-truth confirmation of modeled attenuation and can inform the detection efficiency of lightning location networks. This analysis also paves the way for real-time VLF attenuation mapping in the EIWG. **6 and 10 Sep 2017**

Comparing proton fluxes of central meridian SEP events with those predicted by SOLPENCO.

Aran, A., B. Sanahuja, and D. Lario.
Adv. Space Res., 42, 1492–1499, **2008**,
http://sci-hub.se/10.1016/j.asr.2007.08.003

We have developed an operational code, SOLPENCO, that can be used for space weather prediction schemes of solar energetic particle (SEP) events. SOLPENCO provides proton differential flux and cumulated fluence profiles from the onset of the event up to the arrival of the associated traveling interplanetary shock at the observer's position (either 1.0 or 0.4 AU). SOLPENCO considers a variety of interplanetary scenarios where the SEP events develop. These scenarios include solar longitudes of the parent solar event ranging from E75 to W90, transit speeds of the associated shock ranging from 400 to 1700 km s_1, proton energies ranging from 0.125 to 64 MeV, and interplanetary conditions for the energetic particle transport characterized by specific mean free paths. We compare the results of SOLPENCO with flux measurements of a set of SEP events observed at 1 AU that fulfill the following four conditions: (1) the association between the interplanetary shock observed at 1 AU and the parent solar event is well established; (2) the heliolongitude of the active region site is within 30_ of the Sun–Earth line; (3) the event shows a significant proton flux increase at energies below 96 MeV; (4) the pre-event intensity background is low. The results are discussed in terms of the transit velocity of the shock and the proton energy. We draw conclusions about both the use of SOLPENCO as a prediction tool and the required improvements to make it useful for space weather purposes. **See** http://dev.sepem.oma.be/help/solpenco2_intro.html

SOLPEN CO: a solar particle engineering code.

Aran, A., B. Sanahuja, and D. Lario.
Adv. Space Res., 37, 1240–1246, **2006**,
http://sci-hub.se/10.1016/j.asr.2005.09.019

We present SOLPENCO (SOLar Particle ENgineering COde), the first step towards an operational tool able to quantitatively predict proton flux and fluence profiles of solar energetic particle (SEP) events associated with interplanetary shocks. The main components of this code are the following: a data base containing synthetic proton flux and fluence profiles for a set of 448 different scenarios at 1 AU and at 0.4 AU, for proton energies ranging from 0.125 to 64 MeV; and a user-friendly interface which permits rapid acquisition, by interpolation, of the flux and cumulative fluence profiles in the upstream part of an SEP event for a given solar-interplanetary scenario selected by the user (from among 697,800 cases). SOLPENCO also provides an estimate for the transit time and average speed of the CME-driven shock. We have started the validation of the outputs of this code by comparing them with several observed and modeled SEP events. As an example, we discuss here the case of the 4–6 April 2000 event. The main conclusions are that the code fits well the peak flux for several energy channels, and that the average parameters used to synthesize the flux and fluence profiles must be studied in more detail by performing a statistical study with a large set of observed and modeled SEP scenarios.

Fluxes and fluences of SEP events derived from SOLPENCO

A. **Aran**1, B. Sanahuja2,1, and D. Lario3
Ann. Geophys., 23, 3047-3053, **2005**
sci-hub.se/10.5194/angeo-23-3047-2005

We have developed aran04 a tool for rapid predictions of proton flux and fluence profiles observed during gradual solar energetic particle (SEP) events and upstream of the associated traveling interplanetary shocks. This code, named SOLPENCO (for SOLar Particle ENgineering COde), contains a data base with a large set of interplanetary scenarios under which SEP events develop. These scenarios are basically defined by the solar longitude of the parent solar activity, ranging from E75 to W90, and by the position of the observer, located at 0.4 AU or at 1.0 AU, from the Sun. We are now analyzing the performance and reliability of SOLPENCO. We address here two features of SEP events especially relevant to space weather purposes: the peak flux and the fluence. We analyze how the peak flux and the fluence of the synthetic profiles generated by SOLPENCO vary as a function of the strength of the CME-driven shock, the heliolongitude of the solar parent activity and the particle energy considered. In particular, we comment on the dependence of the fluence on the radial distance of the observer (which does not follow an inverse square law), and we draw conclusions about the influence of the shock as a particle accelerator in terms of its evolving strength and the heliolongitude of the solar site where the SEP event originated.

Introduction to the physics of solar eruptions and their space weather impact

Introduction

Vasilis **Archontis**, Loukas Vlahos

Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences v. 377 Issue 2148 Article ID:20190152 **2019**

https://arxiv.org/pdf/1905.08361.pdf

https://royalsocietypublishing.org/doi/pdf/10.1098/rsta.2019.0152

The physical processes, which drive powerful solar eruptions, play an important role in our understanding of the Sun-Earth connection. In this Special Issue, we firstly discuss how magnetic fields emerge from the solar interior to the solar surface, to build up active regions, which commonly host large-scale coronal disturbances, such as coronal mass ejections (CMEs). Then, we discuss the physical processes associated with the driving and triggering of these eruptions, the propagation of the large-scale magnetic disturbances through interplanetary space and the interaction of CMEs with Earth's magnetic field. The acceleration mechanisms for the solar energetic particles related to explosive phenomena (e.g. flares and/or CMEs) in the solar corona are also discussed. The main aim of this Issue, therefore, is to encapsulate the present state-of-the-art in research related to the genesis of solar eruptions and their space-weather implications. This article is part of the theme issue 'Solar eruptions and their space weather impact'.

Enhanced Radiation Levels at Aviation Altitudes and Their Relationship to Plasma Waves in the Inner Magnetosphere

Homayon **Aryan**, Jacob Bortnik, W. Kent Tobiska, Piyush Mehta, Rashmi Siddalingappa

Space Weather Volume21, Issue10 October **2023** e2023SW003477

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2023SW003477

It is believed that galactic cosmic rays and solar energetic particles are the two major sources of ionizing radiation. However, the radiation source may also be due to relativistic electrons that are associated with precipitation from the Van Allen radiation belts. In this study, we use Automated Radiation Measurements for Aerospace Safety (ARMAS) measurements to investigate the precipitation mechanism of energetic radiation belt electrons. ARMAS instruments are flown on agency-sponsored (NASA, National Oceanic and Atmospheric Administration, National Science Foundation, Federal Aviation Administration, DOE) flights, commercial space transportation companies and airliners (>9 km) in automated radiation collection mode. We identified magnetic conjunction events between ARMAS and NASA's Van Allen Probes to study the highly variable, dynamic mesoscale radiation events observed by ARMAS instruments at aviation altitudes and their relationship to various plasma waves in the inner magnetosphere measured by the Van Allen Probes. The results show that there is a strong correlation between dose rates observed by ARMAS and plasmaspheric hiss wave power measured by the Van Allen Probes, but no such relationship with electromagnetic ion cyclotron waves and only a modest correlation with whistler mode chorus waves. These results suggest that the space environment could have a potentially significant effect on passenger safety.

Continuous In-Situ and Remote Sun Observation for Space Weather Monitoring and Mitigation of Infrastructure Threats Through an Optimized Heliocentric Satellite Constellation

Leonidas **Askianakis**

2024

https://arxiv.org/pdf/2412.07777

Although vital for life on Earth, solar activity poses questions and increasing threats to humanity due to the Sun's unknown dynamics, intensified by our dependence on terrestrial and space-based infrastructure. This situation is compounded by significant gaps in our understanding of space weather phenomena, the Sun's magnetic field, and the need for rapid responses to unpredicted solar events. To address these issues, an optimized heliocentric satellite constellation is proposed that leverages satellites in an Elliptical Walker Constellation. This system offers (among others) equally distributed arguments of periapsis separations and cross-coupled true anomalies with respect to the Sun-centric coordinate frame. In this paper it is also demonstrated that this strategic multi-spacecraft configuration makes it possible to distinguish spatial and temporal changes in solar wind phenomena, reconstruct, in 3D, Coronal Mass Ejections (CMEs), predict which space or ground-based infrastructure and when it will be affected by CMEs, maintain continuous coverage of the critical Sun-Earth line throughout the mission's duration, and protect future missions by providing simultaneously in-situ and remote measurements from small and cost-effective satellites.

Stellar Proton Event-induced surface radiation dose as a constraint on the habitability of terrestrial exoplanets

Dimitra **Atri**

MNRAS Letters **2019**

https://arxiv.org/pdf/1910.09871.pdf

The discovery of terrestrial exoplanets orbiting in habitable zones around nearby stars has been one of the significant developments in modern astronomy. More than a dozen such planets, like Proxima Centauri b and TRAPPIST-1 e, are in close-in configurations and their proximity to the host star makes them highly sensitive to stellar activity. Episodic events such as flares have the potential to cause severe damage to close-in planets, adversely impacting their habitability. Flares on fast rotating young M stars occur up to 100 times more frequently than on G-type stars which makes their planets even more susceptible to stellar activity. Stellar Energetic Particles (SEPs) emanating from Stellar Proton Events (SPEs) cause atmospheric damage (erosion and photochemical changes), and produce secondary particles, which in turn results in enhanced radiation dosage on planetary surfaces. We explore the role of SPEs and planetary factors in determining planetary surface radiation doses. These factors include SPE fluence and spectra, and planetary column density and magnetic field strength. Taking particle spectra from 70 major solar events (observed between 1956 and 2012) as proxy, we use the GEANT4 Monte Carlo model to simulate SPE interactions with exoplanetary atmospheres, and we compute surface radiation dose. We demonstrate that in addition to fluence, SPE spectrum is also a crucial factor in determining the surface radiation dose. We discuss the implications of these findings in constraining the habitability of terrestrial exoplanets.

NOAA Space Weather Prediction Center Radiation Advisories for the International Civil Aviation Organization

H. M. **Bain**, K. Copeland, T. G. Onsager, R. A. Steenburgh
Space Weather Volume21, Issue7 July **2023** e2022SW003346
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022SW003346
The National Oceanic and Atmospheric Administration's Space Weather Prediction Center (NOAA/SWPC) issues several solar radiation storm products: the long standing proton Warnings and Alerts that are based on particle intensity levels observed by the Geostationary Operational Environmental Satellites; and the more recent International Civil Aviation Organization (ICAO) radiation advisories which specify effective dose rates at aviation flight levels. SWPC ICAO advisories are supported by the U.S. Federal Aviation Administration (FAA) CARI-7A model. In this paper we use CARI-7A modeling results for the Ground Level Enhancement 69 (GLE69) solar radiation storm which occurred on the **20th of January 2005** to demonstrate the ICAO advisory format. For the onset and peak of GLE69, we find that a severe (SEV) radiation advisory would have been issued for altitudes above 32,000 ft, for polar and mid latitude regions of the northern and southern hemisphere. At lower altitudes, down to 25,000 ft, the moderate (MOD) radiation threshold would have been exceeded. In total, 10 ICAO radiation advisories would have been issued over 6.5 hr. From the retrospective modeling of GLE69, and feedback from users, we identify ways in which the ICAO advisories should be improved.

Improved Space Weather Observations and Modeling for Aviation Radiation

Hazel **Bain**, T Onsager, C Mertens, K Copeland, E Benton, J Clem, et al.
Front. Astron. Space Sci. 10 :1149014. **2023** doi: 10.3389/fspas.2023.1149014
https://www.frontiersin.org/articles/10.3389/fspas.2023.1149014/full
https://www.frontiersin.org/articles/10.3389/fspas.2023.1149014/pdf
In recent years there has been a growing interest from the aviation community for space weather radiation forecasts tailored to the needs of the aviation industry. In 2019 several space weather centers began issuing advisories for the International Civil Aviation Organization alerting users to enhancements in the radiation environment at aviation flight levels. Due to a lack of routine observations, radiation modeling is required to specify the dose rates experienced by flight crew and passengers. While mature models exist, support for key observational inputs and further modeling advancements are needed. Observational inputs required from the ground-based neutron monitor network must be financially supported for research studies and operations to ensure real-time data is available for forecast operations and actionable end user decision making. An improved understanding of the geomagnetic field is required to reduce dose rate uncertainties in regions close to the open/closed geomagnetic field boundary, important for flights such as those between the continental US and Europe which operate in this region. Airborne radiation measurements, which are crucial for model validation and improvement, are lacking, particularly during solar energetic particle events. New measurement campaigns must be carried out to ensure progress and in situ atmospheric radiation measurements made available for real-time situational awareness. Furthermore, solar energetic particle forecasting must be improved to move aviation radiation nowcasts to forecasts in order to meet customer requirements for longer lead times for planning and mitigation.

A Summary of NOAA Space Weather Prediction Center Proton Event Forecast Performance and Skill

H. M. **Bain**, R. A. Steenburgh, T. G. Onsager, E. M. Stitely
Space Weather **Volume19, Issue7** e2020SW002670 May **2021**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020SW002670

https://doi.org/10.1029/2020SW002670
The effects of solar radiation storms at Earth are felt across a number of technology-based industries. Energetic particles present during these storms impact electrical components on spacecraft, disrupt high frequency (HF) radio communications, and pose a radiation risk for passengers and crew on polar flight routes, as well as for astronauts. An essential aspect of space weather forecasting is therefore to predict the occurrence and properties of a solar proton event before it occurs. In this paper, we review radiation storm products issued by the National Oceanic and Atmospheric Administration's Space Weather Prediction Center (NOAA SWPC) during Solar Cycles 23 and 24. These include three-day probabilistic proton event forecasts and short-term Warning and Alert hazard products. We present performance metrics and forecast skill scores for SWPC probabilistic forecasts and Warning products, which can be used as a benchmark for assessing the performance of radiation storm forecast models. **21 Apr 2002, 7 Sep 2005**

Solar-Terrestrial Data Science: Prior Experience and Future Prospects **Review**
Daniel N. **Baker***
Front. Astron. Space Sci., 02 October **2020** |
https://doi.org/10.3389/fspas.2020.540133
https://www.frontiersin.org/articles/10.3389/fspas.2020.540133/full
Acquisition of relatively large data sets based on measurements in the interplanetary medium, throughout Earth's magnetosphere, and from ground-based platforms has been a hallmark of the heliophysics discipline for several decades. Early methods of time series analysis with such datasets revealed key causal physical relationships and led to successful forecast models of magnetospheric substorms and geomagnetic storms. Applying neural network methods and linear prediction filtering approaches provided tremendous insights into how solar wind-magnetosphere-ionosphere coupling worked under various forcing conditions. Some applications of neural net and related methods were viewed askance in earlier times because it was not obvious how to extract or infer the underlying physics of input-output relationships. Today, there are powerful new methods being developed in the data sciences that harken back to earlier successful specification and forecasting methods. This paper reviews briefly earlier work and looks at new prospects for heliophysics prediction methods.

Space Weather Effects in the Earth's Radiation Belts **Review**
D. N. **Baker,** P. J. Erickson, J. F. Fennell, J. C. Foster, A. N. Jaynes, P. T. Verronen
Space Science Reviews February **2018**, 214:17
https://link.springer.com/content/pdf/10.1007%2Fs11214-017-0452-7.pdf
The first major scientific discovery of the Space Age was that the Earth is enshrouded in toroids, or belts, of very high-energy magnetically trapped charged particles. Early observations of the radiation environment clearly indicated that the Van Allen belts could be delineated into an inner zone dominated by high-energy protons and an outer zone dominated by high-energy electrons. The energy distribution, spatial extent and particle species makeup of the Van Allen belts has been subsequently explored by several space missions. Recent observations by the NASA dual-spacecraft Van Allen Probes mission have revealed many novel properties of the radiation belts, especially for electrons at highly relativistic and ultra-relativistic kinetic energies. In this review we summarize the space weather impacts of the radiation belts. We demonstrate that many remarkable features of energetic particle changes are driven by strong solar and solar wind forcings. Recent comprehensive data show broadly and in many ways how high energy particles are accelerated, transported, and lost in the magnetosphere due to interplanetary shock wave interactions, coronal mass ejection impacts, and high-speed solar wind streams. We also discuss how radiation belt particles are intimately tied to other parts of the geospace system through atmosphere, ionosphere, and plasmasphere coupling. The new data have in many ways rewritten the textbooks about the radiation belts as a key space weather threat to human technological systems. **20 November 2003 , 17 March 2013, 2013-10-08, 17 March 2015**

Resource Letter SW1: Space Weather **Review**
Daniel N. **Baker**, Louis J. Lanzerotti
American Journal of Physics 84, 166 (**2016**);
https://doi.org/10.1119/1.4938403
https://aapt.scitation.org/doi/pdf/10.1119/1.4938403
This Resource Letter describes the phenomena and effects on technological systems that are known collectively as space weather. A brief history of the topic is provided, and the scientific understandings of drivers for such phenomena are discussed. The impacts of space disturbances are summarized, and the strategies for dealing with space weather threats are examined. The Resource Letter concludes with description of approaches that have been proposed to deal with threats to our increasingly technological society.

Capability of Geomagnetic Storm Parameters to Identify Severe Space Weather

N. **Balan**1,2, Qing-He Zhang1, Zanyang Xing1, R. Skoug3, K. Shiokawa4, H. Lühr5, S. Tulasi Ram6, Y. Otsuka4, and Lingxin Zhao1
2019 ApJ 887 51
sci-hub.se/10.3847/1538-4357/ab5113
The paper investigates the capability of geomagnetic storm parameters in the disturbance storm-time (Dst), Kp, and AE indices to distinguish between severe space weather (SvSW) that causes the reported electric power outages and/or telecommunication failures and normal space weather (NSW) that does not cause these severe effects in a 50 yr period (1958–2007). The parameters include the storm intensities DstMin (minimum Dst during the main phase, MP, of the storm), (dDst/dt)MPmax, Kpmax, and AEmax. In addition, the impulsive parameter $\mathrm{IpsDst} = (-1/T_{\mathrm{MP}}) \int_{\mathrm{TMP}} |\mathrm{Dst_{MP}}| dt$ is derived for the storms that are automatically identified in the Kyoto Dst and USGS $\mathrm{Dst}.\int_{\mathrm{TMP}} |\mathrm{Dst_{MP}}| dt$ is the integral of the modulus of the Dst from onset of the MP (MPO) to the DstMin. T MP is the MP duration from MPO to DstMin. The corresponding mean values $\langle \mathrm{Kp_{MP}} \rangle$ and $\langle \mathrm{AE_{MP}} \rangle$ are also calculated. Regardless of the significant differences in the storm parameters between the two Dst indices, the IpsDst in both indices seems to identify four of the five SvSW events (and the Carrington event) in more than 750 NSW events that have been reported to have occurred in 1958–2007, while all other parameters separate one or two SvSWs from the NSWs. Using the Kyoto IpsDst threshold of −250 nT, we demonstrate a 100% true SvSW identification rate with only one false NSW. Using the false NSW event (1972 August 4), we investigate whether using a higher resolution Dst might result in a more accurate identification of SvSWs. The mechanism of the impulsive action leading to large IpsDst and SvSW involves the coincidence that the fast interplanetary coronal mass ejection velocity V contains its shock (or front) velocity ΔV and large interplanetary magnetic field Bz southward covering ΔV. **1972 August 4, 2003 Oct 29-30, 2003 November 20**
Table

Ionospheric response to solar and interplanetary disturbances: a Swarm perspective
G. **Balasis**, C. Papadimitriou and A. Z. Boutsi
Philosophical Transactions of the Royal Society A v. 377 Issue 2148 Article ID: 20180098 **2019**
https://royalsocietypublishing.org/doi/pdf/10.1098/rsta.2018.0098
The ionospheric response to solar and interplanetary disturbances has been the subject of intense study for several decades. For 5 years now, the European Space Agency's Swarm fleet of satellites surveys the Earth's topside ionosphere, measuring magnetic and electric fields at low-Earth orbit with unprecedented detail. Herein, we study in situthe ionospheric response in terms of the occurrence of plasma instabilities based on 2 years of Swarm observations. Plasma instabilities are an important element of space weather because they include irregularities like the equatorial spread F events, which are responsible for the disruption of radio communications. Moreover, we focus on three out of the four most intense geospace magnetic storms of solar cycle 24 that occurred in 2015, including the St Patrick's Day event, which is the strongest magnetic storm of the present solar cycle. We examine the associated ionospheric response at Swarm altitudes through the estimation of a Swarm Dst-like index. The newly proposed Swarm derived Dst index may be suitable for space weather applications.

Updated verification of the Space Weather Prediction Center's solar energetic particle prediction model
Christopher C. **Balch**
SPACE WEATHER, VOL. 6, S01001, doi:10.1029/2007SW000337, **2008**
http://sci-hub.cc/10.1029/2007SW000337
This paper evaluates the performance of an operational proton prediction model currently being used at NOAA's Space Weather Prediction Center. The evaluation is based on proton events that occurred between 1986 and 2004. Parameters for the associated solar events determine a set of necessary conditions, which are used to construct a set of control events. Model output is calculated for these events and performance of the model is evaluated using standard verification measures. For probability forecasts we evaluate the accuracy, reliability, and resolution and display these results using a standard attributes diagram. We identify conditions for which the model is systematically inaccurate. The probability forecasts are also evaluated for categorical forecast performance measures. We find an optimal probability and we calculate the false alarm rate and probability of detection at this probability. We also show results for peak flux and rise time predictions. These findings provide an objective basis for measuring future improvements.

Galactic Cosmic Ray induced absorbed dose rate in deep space – Accounting for detector size, shape, material, as well as for the solar modulation
Saša **Banjac**1*, Lars Berger1, Sönke Burmeister1, Jingnan Guo1,2, Bernd Heber1, Konstantin Herbst1and Robert Wimmer-Schweingruber1
J. Space Weather Space Clim. **2019**, 9, A14

https://www.swsc-journal.org/articles/swsc/pdf/2019/01/swsc180075.pdf
Depending on the radiation field, the absorbed dose rate can depend significantly upon the size of the detectors or the phantom used in the models. In deep space (interplanetary medium) the radiation field is on avarage dominated by Galactic Cosmic Ray (GCR) nuclei. Here, the deep space dose rate that a typical small silicon slab detector measures is compared to a larger phantom corresponding to an ICRU sphere with a 15 cm radius composed of water. To separate and understand respective effects from the composition, size and shape differences in the detectors, this comparison is implemented in several steps. For each phantom, the absorbed dose rate due to GCR nuclei up to Z = 28, as a function of solar modulation conditions, is calculated.
The main components of the GCR flux are protons, followed by helium nuclei and electrons, with Z > 2 nuclei accounting for approximately 1% of the total number of particles. Among the light nuclei with Z > 2, most abundant ones are C, N and O. In this study, we use the GEANT4 model to calculate the absorbed dose (energy deposited as ionization, divided by mass) due to the GCR flux provided by the Badhwar-O'Neill 2010 (BON-10) model. Furthermore, we investigate how the determined absorbed dose rate changes throughout the solar cycle by varying the GCR models from solar minimum to solar maximum conditions. The developed model is validated against the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) microdosimeter measurements. In our current approach, we do not consider the effects of shielding, which will always be present under realistic scenarios.
A second goal of this study is to quantify the contribution of each Z = 1, …, 28 GCR nuclei to absorbed dose rate, in relation to the phantom characteristics. For each Z we determine the most relevant energy range in the GCR spectra for absorbed dose rate estimations. Furthermore, we calculate a solar modulation dependent conversion factor to convert absorbed dose rate measured in silicon to absorbed dose rate in water. This information will improve our understanding of the radiation environment due to GCR in the near-Earth deep space and also benefit further modeling efforts by limiting the number and energy range of primary particle species that have to be considered.

What can the annual 10Be solar activity reconstructions tell us about historic space weather?

Luke **Barnard**1*, Ken G. McCracken2, Mat J. Owens1 and Mike Lockwood
J. Space Weather Space Clim. **2018**, 8, A23
https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc170075.pdf
Context: Cosmogenic isotopes provide useful estimates of past solar magnetic activity, constraining past space climate with reasonable uncertainty. Much less is known about past space weather conditions. Recent advances in the analysis of 10Be byMcCracken & Beer (2015, Sol Phys 290: 305–3069) (MB15) suggest that annually resolved 10Be can be significantly affected by solar energetic particle (SEP) fluxes. This poses a problem, and presents an opportunity, as the accurate quantification of past solar magnetic activity requires the SEP effects to be determined and isolated, whilst doing so might provide a valuable record of past SEP fluxes.
Aims: We compare the MB15 reconstruction of the heliospheric magnetic field (HMF), with two independent estimates of the HMF derived from sunspot records and geomagnetic variability. We aim to quantify the differences between the HMF reconstructions, and speculate on the origin of these differences. We test whether the differences between the reconstructions appear to depend on known significant space weather events.
Methods: We analyse the distributions of the differences between the HMF reconstructions. We consider how the differences vary as a function of solar cycle phase, and, using a Kolmogorov-Smirnov test, we compare the distributions under the two conditions of whether or not large space weather events were known to have occurred.
Results: We find that the MB15 reconstructions are generally marginally smaller in magnitude than the sunspot and geomagnetic HMF reconstructions. This bias varies as a function of solar cycle phase, and is largest in the declining phase of the solar cycle. We find that MB15's excision of the years with very large ground level enhancement (GLE) improves the agreement of the 10Be HMF estimate with the sunspot and geomagnetic reconstructions. We find no statistical evidence that GLEs, in general, affect the MB15 reconstruction, but this analysis is limited by having too few samples. We do find evidence that the MB15 reconstructions appear statistically different in years with great geomagnetic storms.

The Loss of Starlink Satellites in February 2022: How Moderate Geomagnetic Storms Can Adversely Affect Assets in Low-Earth Orbit

Yoshita **Baruah**, Souvik Roy, Suvadip Sinha, Erika Palmerio, Sanchita Pal, Denny M. Oliveira, Dibyendu Nandy
Space Weather Volume22, Issue4 April **2024** e2023SW003716
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2023SW003716
On **3 February 2022**, SpaceX launched 49 Starlink satellites, 38 of which unexpectedly de-orbited. Although this event was attributed to space weather, definitive causality remained elusive because space weather conditions were not extreme. In this study, we identify solar sources of the interplanetary coronal mass ejections that were responsible for the geomagnetic storms around the time of launch of the Starlink satellites and for the first time, investigate their impact on Earth's magnetosphere using magnetohydrodynamic modeling. The model results

demonstrate that the satellites were launched into an already disturbed space environment that persisted over several days. However, on performing comparative satellite orbital decay analyses, we find that space weather alone was not responsible but conspired together with a low-altitude insertion and low satellite mass-to-area ratio to precipitate this unusual loss. Our work bridges space weather causality across the Sun–Earth system—with relevance for space-based human technologies.

Diagnostics of Space Weather Drivers Enabled by Radio Observations **Review**

Tim **Bastian**, Hazel Bain, Bin Chen, Dale Gary, Gregory Fleishman, Lindsay Glesener, Pascal Saint-Hilaire, Colin Lonsdale, Stephen White

White paper submitted to the Astronomy and Astrophysics decadal survey **2019**

https://arxiv.org/pdf/1904.05817.pdf

The Sun is an active star that can have a direct impact on the Earth, its magnetosphere, and the technological infrastructure on which modern society depends. Among the phenomena that drive "space weather" are fast solar wind streams and co-rotating interaction regions, solar flares, coronal mass ejections, the shocks they produce, and the energetic particles they accelerate. Radio emission from these and associated phenomena offer unique diagnostic possibilities that complement those available at other wavelengths. Here, the relevant space weather drivers are briefly described, the potential role of radio observations is outlined, and the requirements of an instrument to provide them are provided: specifically, ultrabroadband imaging spectropolarimetry. The insights provided by radio observations of space weather drivers will not only inform the science of space weather, they will pave the way for new tools for forecasting and "nowcasting" space weather. They will also serve as an important touchstone against which local environment of exoplanets and the impact of "exo-space weather" can be evaluated.

A User's Guide to the Magnetically Connected Space Weather System: A Brief **Review**

Jason **Beedle**, Chris Rura, David Simpson, Hale Cohen, Valmir Moraes Filho, and Vadim Uritsky

Front. Astron. Space Sci., 8:786308. January **2022** | **File**

https://doi.org/10.3389/fspas.2021.786308

https://www.frontiersin.org/articles/10.3389/fspas.2021.786308/full

This article provides a concise review of the main physical structures and processes involved in space weather's interconnected systems, emphasizing the critical roles played by magnetic topology and connectivity. The review covers solar drivers of space weather activity, the heliospheric environment, and the magnetospheric response, and is intended to address a growing cross-disciplinary audience interested in applied aspects of modern space weather research and forecasting. The review paper includes fundamental facts about the structure of space weather subsystems and special attention is paid to extreme space weather events associated with major solar flares, large coronal mass ejections, solar energetic particle events, and intense geomagnetic perturbations and their ionospheric footprints. This paper aims to be a first step towards understanding the magnetically connected space weather system for individuals new to the field of space weather who are interested in the basics of the space weather system and how it affects our daily lives. **9 Feb 2015**

SWELTO -- Space WEather Laboratory in Turin Observatory

A. Bemporad, L. Abbo, D. Barghini, C. Benna, R. Biondo, D. Bonino, G. Capobianco, F. Carella, A. Cora, S. Fineschi, F. Frassati, D. Gardiol, S. Giordano, A. Liberatore, S. Mancuso, A. Mignone, S. Rasetti, F. Reale, A. Riva, F. Salvati, R. Susino, A. Volpicelli, L. Zangrilli

INAF Technical Reports series, num. 40, **2020** (https://openaccess.inaf.it/handle/20.500.12386/27715)

https://arxiv.org/pdf/2101.07037.pdf

SWELTO -- Space WEather Laboratory in Turin Observatory is a conceptual framework where new ideas for the analysis of space-based and ground-based data are developed and tested. The input data are (but not limited to) remote sensing observations (EUV images of the solar disk, Visible Light coronagraphic images, radio dynamic spectra, etc...), in situ plasma measurements (interplanetary plasma density, velocity, magnetic field, etc...), as well as measurements acquired by local sensors and detectors (radio antenna, fluxgate magnetometer, full-sky cameras, located in OATo). The output products are automatic identification, tracking, and monitoring of solar stationary and dynamic features near the Sun (coronal holes, active regions, coronal mass ejections, etc...), and in the interplanetary medium (shocks, plasmoids, corotating interaction regions, etc...), as well as reconstructions of the interplanetary medium where solar disturbances may propagate from the Sun to the Earth and beyond. These are based both on empirical models and numerical MHD simulations. The aim of SWELTO is not only to test new data analysis methods for future application for Space Weather monitoring and prediction purposes, but also to procure, test and deploy new ground-based instrumentation to monitor the ionospheric and geomagnetic responses to solar activity. Moreover, people involved in SWELTO are active in outreach to disseminate the topics related with Space Weather to students and the general public.

Simultaneous Multivariate Forecast of Space Weather Indices using Deep Neural Network Ensembles

Bernard **Benson**, Edward Brown, Stefano Bonasera, Giacomo Acciarini, Jorge A. Pérez-Hernández, Eric Sutton, Moriba K. Jah, Christopher Bridges, Meng Jin, Atılım Güneş Baydin

Fourth Workshop on Machine Learning and the Physical Sciences (NeurIPS **2021**)

https://arxiv.org/ftp/arxiv/papers/2112/2112.09051.pdf

Solar radio flux along with geomagnetic indices are important indicators of solar activity and its effects. Extreme solar events such as flares and geomagnetic storms can negatively affect the space environment including satellites in low-Earth orbit. Therefore, forecasting these space weather indices is of great importance in space operations and science. In this study, we propose a model based on long shortterm memory neural networks to learn the distribution of time series data with the capability to provide a simultaneous multivariate 27-day forecast of the space weather indices using time series as well as solar image data. We show a 30–40% improvement of the root mean-square error while including solar image data with time series data compared to using time series data alone. Simple baselines such as a persistence and running average forecasts are also compared with the trained deep neural network models. We also quantify the uncertainty in our prediction using a model ensemble.

Ionospheric response to the X9.3 Flare on 6 September 2017 and its implication for navigation services over Europe

J. **Berdermann**, M. Kriegel, D. Banyś, F. Heymann, M. M. Hoque, V. Wilken, C. Borries, A. Hesselbarth, N. Jakowski

Space Weather **2018**

https://doi.org/10.1029/2018SW001933

On 6 September, 2017, a X-class flare of the magnitude 9.3 occurred around noon UT, being the strongest flare event in a decade. The flare itself was the highlight of a quite interesting phase of solar-terrestrial interactions caused by the active region known as the Catania sunspot group 46 or active region number 2673 on the NOAA catalogue. From 3 to 13 September 2017 strong flare activities occured, accompanied by a number of radio bursts and earthward-directed coronal mass ejections (CMEs). Solar wind influences at Earth were modest during the flare activity and limited to the polar regions (Linty et al, 2018). But, the strong X9.3-flare itself had impacts on the dayside ionosphere causing some problems in navigation services as we present within this paper. The event data observed and analysed gives us the opportunity to improve our understanding of strong and extreme space weather events and allows us to distinguish between the influence of the different event classes on our technological infrastructure within periods of strong solar activity. Here we will discuss our observations with special focus on the X9.3 flare event and provide examples how the flare itself influenced services in the domains of aviation and maritime navigation in the European sector.

The Thermosphere Is a Drag: The 2022 Starlink Incident and the Threat of Geomagnetic Storms to Low Earth Orbit Space Operations

T. E. **Berger**, M. Dominique, G. Lucas, M. Pilinski, V. Ray, R. Sewell, E. K. Sutton, J. P. Thayer, E. Thiemann

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https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022SW003330

On **03 February 2022**, SpaceX launched 49 Starlink satellites, 38 of which re-entered the atmosphere on or about 07 February 2022 due to unexpectedly high atmospheric drag. We use empirical model (NRLMSIS, JB08, and HASDM) outputs as well as solar extreme ultraviolet occultation and high-fidelity accelerometer data to show that thermospheric density was at least 20%–30% higher at 210 km relative to the 9 days prior to the launch due to consecutive geomagnetic storms related to solar eruptions from NOAA AR12936 on 29 January 2022. We model the orbital altitude and in-track position of a Starlink-like satellite in a low-drag configuration at 200 km during minor (G1) and extreme (G5) geomagnetic storms to show that an extreme storm would have at least a factor of two higher impact, with cumulative in-track errors on the order of 10,000 km after a 5-day duration extreme storm. Comparison of the JB08 and NRL MSIS models relative to the HASDM model during modeled historical minor and extreme geomagnetic storms shows that in-track errors on the order of 100 km per day at 250 km, decreasing to cumulative errors on the order of 1 km per day at 550 km during geomagnetic storms. We conclude that full-physics, data assimilative, coupled models of the magnetosphere and upper atmosphere, as well as new operational satellite missions providing “nowcasting” data to launch controllers, space traffic coordinators, and satellite operators, are needed to prevent similar—or worse—orbital system impacts during future geomagnetic storms.

Long term variations of galactic cosmic radiation on board the International Space Station, on the Moon and on the surface of Mars

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J. Space Weather Space Clim. **2020**, 10, 34
https://www.swsc-journal.org/articles/swsc/pdf/2020/01/swsc200013.pdf
The radiation environment in free space and the related radiation exposure is seen as one of the main health detriments for future long-duration human exploration missions beyond Low Earth Orbit (LEO). The steady flux of energetic particles in the galactic cosmic radiation (GCR) produces a low dose-rate radiation exposure, which is heavily influenced by several factors including the solar cycle, the presence of an atmosphere, relevant magnetic fields (as on Earth) and of course by the relevant spacecraft shielding. Investigations of the GCR variations over the course of a solar cycle provide valuable data for exploration mission planning and for the determination of the radiation load received due to the GCR environment. Within the current work these investigations have been performed applying three datasets generated on board the International Space Station (ISS) with the DOSTEL instruments in the frame of the DOSIS and DOSIS-3D projects, with the CRaTER instrument in a Moon orbit and with the MSL-RAD instrument on the way to and on the surface of Mars. To derive GCR dose contributions on board the ISS two procedures have been developed separating the contributions from GCR from passing's through the South Atlantic Anomaly (SAA), as well as ways to extrapolate the GCR dose measured on board the ISS to free space based on various ranges of the McIlwain L-shell parameter. At the end we provide a dataset spanning the timeframe for GCR measurements on the ISS (2009–2011 & 2012–2019), Moon (2009–2019) and Mars (2012–2019), thereby covering the time span from the deep minimum of solar cycle 23, the ascending phase and maximum of solar cycle 24, and the descending phase of cycle 24, which is ongoing at the time of this writing.

Flying Through Uncertainty **Review**

T. E. **Berger** , M. J. Holzinger , E. K. Sutton , J. P. Thayer
Space Weather Volume18, Issue1 January **2020** e2019SW002373
https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2019SW002373
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019SW002373
Space weather is the main source of uncertainty in the position of all objects in low Earth orbit (LEO) below about 1,000 km. The main impact is strong variation in the neutral density of the thermosphere as it responds to radiative inputs from the Sun in the extreme ultraviolet wavelength range, energetic particle precipitation in the high-latitude auroral zones, and global-scale electrical currents generated during geomagnetic storms. Waves and instabilities from the lower atmosphere can also influence thermospheric density in complex ways. The variation in neutral density leads to variable drag forces on satellites flying through the thermosphere, which in turn causes orbital track changes. We currently lack the ability to accurately model and predict the neutral density changes in the thermosphere in response to space weather inputs. Operational empirical models of thermospheric density are inaccurate during space weather events, and mandate that LEO orbital tracks carry large "error ellipsoids" around all objects to account for positional uncertainty. This leads to many more "conjunction" warnings than necessary as large error ellipsoids are frequently calculated to intersect in orbit. As the LEO domain becomes more crowded with the advent of commercial "megaconstellations" we face a growing challenge to reduce orbital uncertainties by developing whole atmosphere models to enable timely and accurate forecasts of thermospheric conditions. We recommend that researchers, forecasters, and policy makers coordinate to ensure that space weather research and forecasting is tightly integrated into upcoming changes to the operational Space Traffic Management system.

The Solar Polar Observing Constellation (SPOC) Mission: research and operational monitoring of space weather from polar heliocentric orbits

Berger, T. E.; Bosanac, N.; Smith, T. R.; Duncan, N. A.; Wu, G.; Turner, E.; Hurlburt, N.; Korendyke, C.
American Geophysical Union, Fall Meeting 2019, abstract #SH43F-3352, **2019**
https://ui.adsabs.harvard.edu/abs/2019AGUFMSH43F3352B/abstract
The Sun's polar regions remain largely unobserved and yet understanding and monitoring of the magnetic field, convective flows, and coronal outflow conditions in the solar polar regions are the keys to accurately modeling and forecasting the solar cycle, solar wind conditions, and CME arrival times at Earth. We describe the Solar Polar Observing Constellation (SPOC), a mission to establish continuous high-resolution imaging of solar magnetic field dynamics, high-latitude surface and sub-surface convective flows, and coronal mass ejection tracking from a low-eccentricity polar heliocentric orbit. SPOC will consist of two identical spacecraft, each equipped with a Lockheed Martin Compact Magnetic Imager (CMI, derived from the Solar Dynamics Observatory (SDO) Helioseismic and Magnetic Imager), the Naval Research Laboratory (NRL) Compact Coronagraph (CCOR), and in-situ solar wind and energetic particle instruments. Falcon Heavy launch vehicles will place the SPOC spacecraft into a Jupiter gravitational assist (JGA) heliocentric orbit, achieving an 88-degree ecliptic inclination, with the spacecraft passing over the solar poles within 4 years after launch. Ion engines will subsequently reduce the eccentricity of the orbits to below 0.05 at approximately 0.9 AU within 6 years after launch. Orbital phasing will place the spacecraft over

alternate poles to enable continuous monitoring of the polar regions with operational-level redundancy of systems. The inclusion of CCOR will enable visualization and tracking of coronal mass ejections from above (or below) the ecliptic for the first time, greatly enhancing our ability to forecast CME arrival times at Earth and other planets such as Mars. SPOC combines polar region exploration, high-latitude helioseismology and magnetic imaging, and operational space weather monitoring in a single mission. Along with planned missions to the L1 and L5 Lagrangian points in the ecliptic, SPOC will enable an approach to the long-sought goal of continuous full-sphere measurements of the solar magnetic field, solar wind and CME outflow, and energetic particle flux - a goal that cannot be achieved with observations from the ecliptic plane alone.

Global Diagnostics of Ionospheric Absorption During X-Ray Solar Flares Based on 8- to 20-MHz Noise Measured by Over-the-Horizon Radars

O. I. **Berngardt**, J. M. Ruohoniemi, J.-P. St-Maurice, A. Marchaudon, M. J. Kosch, A. S. Yukimatu, N. Nishitani, S. G. Shepherd, M. F. Marcucci, H. Hu, T. Nagatsuma, M. Lester

Space Weather **2019**
sci-hub.se/10.1029/2018SW002130

An analysis of noise attenuation during 80 solar flares between 2013 and 2017 was carried out at frequencies 8–20 MHz using 34 Super Dual Auroral Radar Network radars and the EKB ISTP SB RAS radar. The attenuation was determined on the basis of noise measurements performed by the radars during the intervals between transmitting periods. The location of the primary contributing ground sources of noise was found by consideration of the propagation paths of radar backscatter from the ground. The elevation angle for the ground echoes was determined through a new empirical model. It was used to determine the paths of the noise and the location of its source. The method was particularly well suited for daytime situations, which had to be limited for the most part to only two crossings through the D region. Knowing the radio path was used to determine an equivalent vertical propagation attenuation factor. The change in the noise during solar flares was correlated with solar radiation lines measured by GOES/XRS, GOES/EUVS, SDO/AIA, SDO/EVE, SOHO/SEM, and PROBA2/LYRA instruments. Radiation in the 1 to 8 Å and near 100 Å are shown to be primarily responsible for the increase in the radionoise absorption, and by inference, for an increase in the D and E region density. The data are also shown to be consistent with a radar frequency dependence having a power law with an exponent of −1.6. This study shows that a new data set can be made available to study D and E regions.

2013/04/11, 2013/05/11, 2013/10/25, 2014/02/25, 2014/03/29, 2014/04/18, 2014/10/19, 2014/11/05, 2014/11/16, 2015/12/23, 2017/04/03

Attenuation of decameter wavelength sky noise during x-ray solar flares in 2013–2017 based on the observations of midlatitude HF radars

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Volume 173, August **2018**, Pages 1-13
https://reader.elsevier.com/reader/sd/F8CA539213879B508A2352165551EDE6140E0B9E58FA294D2AD5C27F005C51A40AD4F14FDD5537E1C1971E6B4F92310A

Based on a joint analysis of data from 10 midlatitude decameter wavelength radars effects are investigated during 80 x-ray flares that occurred in the period 2013–2017. For the investigation nine mid-latitude SuperDARN radars of the northern hemisphere (Adak Island West and East radars, Blackstone radar, Christmas Valley East and West radars, Fort Hays East and West radars, Hokkaido East radar and Wallops radar) and Ekaterinburg coherent decameter radar of ISTP SB RAS are used. All the radars work in the same 8–20 MHz frequency band and have similar hardware and software. During the analysis the temporal dynamics of noise from each of the radar direction and for each flare is investigated separately. As a result, on the basis of about 13000 daily measurements we found a strong anticorrelation between noise power and x-ray flare intensity, indicating that short-wave sky noise can be used to diagnose the ionospheric effects of x-ray solar flares. It is shown that in 88.3% of cases an attenuation of daytime decameter radio noise is observed during solar flares, and the attenuation correlates with the temporal dynamics of the solar flare. The intensity of decameter noise anticorrelates well (the Pearson correlation coefficient better than −0.5) with the shape of the X-ray flare in the daytime (for solar elevation angle >0) in 33% of cases, the average Pearson correlation over the daytime is about −0.34. Median regression coefficient between GOES 0.1–0.8 nm x-ray intensity and daytime sky-noise attenuation is about −4.4·104[dB·m2/Wt]. Thus, it is shown that measurements of the sky noise level at midlatitude decameter radars can be used to study the ionospheric absorption of high-frequency waves in the lower ionosphere during x-ray solar flares. This can be explained by the assumption that the larger part of the decameter sky noise detected by the radars is produced by ground sources at distances of the first propagation hop (~3000 km).

The Great Aurora of 4 February 1872 observed by Angelo Secchi in Rome

Francesco **Berrilli**, Luca Giovannelli

Journal of Space Weather and Space Climate **12**, 3 **2022**
https://arxiv.org/pdf/2201.01171.pdf
https://www.swsc-journal.org/articles/swsc/pdf/2022/01/swsc210083.pdf
Observation of auroras at low latitudes is an extremely rare event typically associated with major magnetic storms due to intense Earth-directed Coronal Mass Ejections. Since these energetic events represent one of the most important components of space weather, their study is of paramount importance to understand the Sun-Earth connection. Due to the rarity of these events, being able to access all available information for the few cases studied is equally important. Especially if we refer to historical periods in which current accurate observations from ground-based instruments or space were not available. Certainly, among these events, we must include the great aurora of February 4, 1872. An event whose effects have been observed in different regions of the Earth. What we could consider today a global event, especially for its effects on the communication systems of the time, such as the transatlantic cable that allowed a connection between the United States and Europe since 1866. In this paper, we describe the main results of the observations and studies carried out by Angelo Secchi at the Observatory of the Roman College and described in his Memoria sull'Aurora Elettrica del 4 Febbraio 1872 for the Notes of the Pontifical Academy of new Lincei. This note is extremely modern both in its multi-instrumental approach to the study of these phenomena and in its association between solar-terrestrial connection and technological infrastructures on the Earth. The Secchi's note definitely represents the first example of analysis and study of an event on a global scale, such as the Atlantic cable, affecting the Earth. What we nowadays call an extreme space weather event.

Solar irradiance, climatic indicators and climate change – An empirical analysis

Asheesh **Bhargawa**, A.K.Singh
Advances in Space Research Volume 64, Issue 1, 1 July **2019**, Pages 271-277
sci-hub.se/10.1016/j.asr.2019.03.018
Since the Sun is the main source of energy for our planet therefore even a slight change in its output energy can make a huge difference in the climatic conditions of the terrestrial environment. The rate of energy coming from the Sun (solar irradiance) might affect our climate directly by changing the rate of solar heating of the Earth and the atmosphere and indirectly by changing the cloud forming processes. In the present paper, based on stability test of Vector Auto Regressive (VAR) model, we have used the impulse response functions and the variance decomposition method for the analysis of climate variability. We have examined the possible connections among the solar irradiance and some climate indicators, viz., the global temperature anomaly, the global mean sea level, the global sea-ice extent and the global precipitation anomaly occurred during last forty years (1978–2017). In our investigation, we have observed that the impact of solar irradiance on the global surface temperature level in next decade will increase by ~4.7% while the global mean sea level will increase about 0.67%. In the meantime, we have noticed about 5.3% decrement in the global sea-ice extent for the next decade. In case of the global precipitation anomaly we have not observed any particular trend just because of the variable climatic conditions. We also have studied the effect of CO_2 as anthropogenic forcing where we have observed that the global temperature in the next decade will increase by 2.7%; mean sea level will increase by 6.4%. Increasing abundance in CO_2 will be responsible for about 0.43% decrease in the sea-ice extent while there will not be any change in the precipitation pattern.

NOAA Space Weather Prediction Center Radiation Advisories for the International Civil Aviation Organization

H. M. **Bain**, K. Copeland, T. G. Onsager, R. A. Steenburgh
Space Weather e2022SW003346 Volume21, Issue7 July **2023**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022SW003346
The National Oceanic and Atmospheric Administration's Space Weather Prediction Center (NOAA/SWPC) issues several solar radiation storm products: the long standing proton Warnings and Alerts that are based on particle intensity levels observed by the Geostationary Operational Environmental Satellites; and the more recent International Civil Aviation Organization (ICAO) radiation advisories which specify effective dose rates at aviation flight levels. SWPC ICAO advisories are supported by the U.S. Federal Aviation Administration (FAA) CARI-7A model. In this paper we use CARI-7A modeling results for the Ground Level Enhancement 69 (GLE69) solar radiation storm which occurred on the 20th of January 2005 to demonstrate the ICAO advisory format. For the onset and peak of GLE69, we find that a severe (SEV) radiation advisory would have been issued for altitudes above 32,000 ft, for polar and mid latitude regions of the northern and southern hemisphere. At lower altitudes, down to 25,000 ft, the moderate (MOD) radiation threshold would have been exceeded. In total, 10 ICAO radiation advisories would have been issued over 6.5 hr. From the retrospective modeling of GLE69, and feedback from users, we identify ways in which the ICAO advisories should be improved.

Summary of the plenary sessions at European Space Weather Week 15: space weather users and service providers working together now and in the future

Suzy **Bingham**1*, Sophie A. Murray2,3, Antonio Guerrero4, Alexi Glover5 and Peter Thorn

J. Space Weather Space Clim., 9 (**2019**) A32

https://www.swsc-journal.org/articles/swsc/pdf/2019/01/swsc190006.pdf

During European Space Weather Week 15 two plenary sessions were held to review the status of operational space weather forecasting. The first session addressed the topic of working with space weather service providers now and in the future, the user perspective. The second session provided the service perspective, addressing experiences in forecasting development and operations. Presentations in both sessions provided an overview of international efforts on these topics, and panel discussion topics arising in the first session were used as a basis for panel discussion in the second session. Discussion topics included experiences during the September 2017 space weather events, cross domain impacts, timeliness of notifications, and provision of effective user education. Users highlighted that a severe space weather event did not necessarily lead to severe impacts for each individual user across the different sectors. Service providers were generally confident that timely and reliable information could be provided during severe and extreme events, although stressed that more research and funding were required in this relatively new field of operational space weather forecasting, to ensure continuation of capabilities and further development of services, in particular improved forecasting targeting user needs. Here a summary of the sessions is provided followed by a commentary on the current state-of-the-art and potential next steps towards improvement of services.

SuperDARN radar-derived HF radio attenuation during the September 2017 solar proton events

Emma C. **Bland**, , Erkka Heino, Michael J. Kosch, Noora Partamies

Space Weather Volume16, Issue10 Pages 1455-1469 **2018**

https://doi.org/10.1029/2018SW001916

Two solar proton events in September 2017 had a significant impact on the operation of the Super Dual Auroral Radar Network (SuperDARN), a global network of high frequency (HF) radars designed for observing F-region ionospheric plasma convection. Strong polar cap absorption (PCA) caused near-total loss of radar backscatter, which prevented the primary SuperDARN data products from being determined for a period of several days. During this interval, the high-latitude and polar cap radars measured unusually-low levels of background atmospheric radio noise. We demonstrate that these background noise measurements can be used to observe the spatial and temporal evolution of the PCA region, using an approach similar to riometry. We find that the temporal evolution of the SuperDARN radar-derived HF attenuation closely follows that of the cosmic noise absorption measured by a riometer. Attenuation of the atmospheric noise up to 10dB at 12MHz is measured within the northern polar cap, and up to 14dB in the southern polar cap, which is consistent with the observed backscatter loss. Additionally, periods of enhanced attenuation lasting 2–4 hours are detected by the mid-latitude radars in response to M- and X-class solar flares. Our results demonstrate that SuperDARN's routine measurements of atmospheric radio noise can be used to monitor 8–20MHz radio attenuation from middle to polar latitudes, which may be used to supplement riometer data and also to investigate the causes of SuperDARN backscatter loss during space weather events.

The Helioseismic and Magnetic Imager (HMI) Vector Magnetic Field Pipeline: SHARPs - Space-Weather HMI Active Region Patches

Bobra, M. G.; Sun, X.; Hoeksema, J. T.; Turmon, M.; Liu, Y.; Hayashi, K.; Barnes, G.; Leka, K. D.

Solar Physics, Volume 289, Issue 9, pp.3549-3578 **2014**

https://arxiv.org/pdf/1404.1879.pdf

A new data product from the Helioseismic and Magnetic Imager (HMI) onboard the Solar Dynamics Observatory (SDO) called Space-weather HMI Active Region Patches (SHARPs) is now available. SDO/HMI is the first space-based instrument to map the full-disk photospheric vector magnetic field with high cadence and continuity. The SHARP data series provide maps in patches that encompass automatically tracked magnetic concentrations for their entire lifetime; map quantities include the photospheric vector magnetic field and its uncertainty, along with Doppler velocity, continuum intensity, and line-of-sight magnetic field. Furthermore, keywords in the SHARP data series provide several parameters that concisely characterize the magnetic-field distribution and its deviation from a potential-field configuration. These indices may be useful for active-region event forecasting and for identifying regions of interest. The indices are calculated per patch and are available on a twelve-minute cadence. Quick-look data are available within approximately three hours of observation; definitive science products are produced approximately five weeks later. SHARP data are available at **jsoc.stanford.edu** and maps are available in either of two different coordinate systems. This article describes the SHARP data products and presents examples of SHARP data and parameters.

Prediction of Radiation Belts Electron Fluxes at a Low Earth Orbit Using Neural Networks With PROBA-V/EPT Data

Edith **Botek**, Viviane Pierrard, Alexandre Winant

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We introduce for the first time the PROBA-V/EPT electron flux data to train a deep learning data-driven model with the purpose of investigating the Earth's radiation belts dynamics. The Long-Short Term Memory Neural Network is employed to predict the electron fluxes between 1 and 8 Earth Radius (RE) along a Low Earth Orbit. Different combinations of time series inputs involving Solar Wind and geomagnetic data are tested, based on previous knowledge of their impact onto the high energy radiation fluxes. Two Energetic Particle Telescope energy channels feed the learning procedure for nonrelativistic (0.5–0.6 MeV) and relativistic (1.0–2.4 MeV) electron fluxes. A good performance of the model employing different time resolutions from hours to days is demonstrated with a correlation of more than 0.9 between the predicted and out-of-sample fluxes, and a prediction efficiency that can attain between 0.6 and 0.9 depending on the L range. The analysis of different input parameters and time resolutions allows to construct the best data set structure and improve the model to identify relevant effects such as dropouts, flux increase and recovery features.

Modelling Geomagnetic Interference on Railway Signalling Track Circuits

D. H. **Boteler**

Space Weather **Volume19, Issue1** January **2021** e2020SW002609
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020SW002609

Misoperation of railway signalling during geomagnetic disturbances has occurred in a number of countries. Railway signals are activated by track circuits that detect the presence of a train in a particular rail section, but geomagnetically induced electric fields can interfere with the track circuit operation, causing the wrong signal to be displayed. This paper develops a new model for track circuit operation that includes the induced geoelectric fields produced by geomagnetic field variations. Rails are modelled as transmission lines with series impedance given by the rail resistance and parallel admittance determined by the current leakage from the rail through the ballast to ground. The transmission line model is then converted into an equivalent-pi circuit for each rail and these are combined with the track circuit power and relay components to form a nodal admittance network for the track circuit. This is used to examine the effect of induced geoelectric fields on track circuit operation. First, an individual track circuit is examined and it is shown how the length, between insulating rail joints, of the individual rails influences the geomagnetic interference voltage produced across the track circuit relay. Then a series of track circuits is considered: a general solution is developed and then the conditions are identified that allow this to be reduced to a simpler solution considering each track circuit individually. This modelling provides insight into the conditions that produce signalling problems and provides the tools to assess the geomagnetic hazard to railway signalling.

A Twenty-First Century View of the March 1989 Magnetic Storm

D.H. **Boteler**

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On March 13, 1989, the largest magnetic storm of the last century caused widespread effects on power systems including a blackout of the Hydro-Québec system. Since then this event has become the archetypal disturbance for examining the geomagnetic hazard to power systems. However, even 30 years on from 1989, the story of exactly what happened in March 1989 is far from complete. This paper re-examines the information available about the March 1989 event and uses this to construct a timeline and description of the space weather phenomena and how they caused the power system effects. The evidence shows that the disturbance was caused by two coronal mass ejections (CMEs): the first associated with a X4.5 flare on March 10 and the second linked to a M7.3 flare on March 12. The arrival of the interplanetary coronal mass ejection (ICME) shock fronts caused storm sudden commencements (SSC) at 01.27 UT and 07.43 UT on March 13. The transit time and speed of the first (second) ICME shock are 54.5 hrs (31.5 hrs) and 760 km/sec (1320 km/sec). Empirical relations are used to estimate solar wind speed and southward IMF, Bs, and give values of v=980 km/sec, Bs=40nT to 60nT at the peak of the storm. Key findings are that the second SSC occurred at the same time as the substorm that impacted the Hydro-Québec system and indicates that external triggering of the substorm may have contributed to a faster substorm onset than might otherwise have occurred. This caused the production of larger geomagnetically induced currents (GIC) that caused the Hydro-Québec blackout. The March 1989 storm had the largest recorded value of the Dst index representing the size of the magnetic storm main phase, but the Hydro-Québec blackout occurred early in the storm

when the Dst value was less disturbed. Only later in the storm did Dst reach its peak value. At this time an expansion of the auroral oval brought disturbances to lower latitudes where they caused power system problems in the US, UK and Sweden.

On the Prediction of >100 MeV Solar Energetic Particle Events Using GOES Satellite Data

Soukaina Filali **Boubrahimi**, Berkay Aydin, Petrus Martens, Rafal Angryk

2017

https://arxiv.org/pdf/1712.03998.pdf

Solar energetic particles are a result of intense solar events such as solar flares and Coronal Mass Ejections (CMEs). These latter events all together can cause major disruptions to spacecraft that are in Earth's orbit and outside of the magnetosphere. In this work we are interested in establishing the necessary conditions for a major geo-effective solar particle storm immediately after a major flare, namely the existence of a direct magnetic connection. To our knowledge, this is the first work that explores not only the correlations of GOES X-ray and proton channels, but also the correlations that happen across all the proton channels. We found that proton channels auto-correlations and cross-correlations may also be precursors to the occurrence of an SEP event. In this paper, we tackle the problem of predicting >100 MeV SEP events from a multivariate time series perspective using easily interpretable decision tree models. **2001-04-02 , 2001-04-15, 2011-04-15**,

TABLE II > 100 MEV SEP EVENT LIST WITH THEIR PARENT EVENTS (CME/FLARE)

TABLE III NON SEP EVENT LIST

Empirical Model of 10-130 MeV Solar Energetic Particle Spectra at 1 AU Based on Coronal Mass Ejection Speed and Direction

Alessandro **Bruno**, Ian G. Richardson

Solar Phys. **2021**

https://arxiv.org/pdf/2101.04234.pdf **File**

We present a new empirical model to predict solar energetic particle (SEP) event-integrated and peak intensity spectra between 10 and 130 MeV at 1 AU, based on multi-point spacecraft measurements from the Solar TErrestrial RElations Observatory (STEREO), the Geostationary Operational Environmental Satellites (GOES) and the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) satellite experiment. The analyzed data sample includes 32 SEP events occurring between 2010 and 2014, with a statistically significant proton signal at energies in excess of a few tens of MeV, unambiguously recorded at three spacecraft locations. The spatial distributions of SEP intensities are reconstructed by assuming an energy-dependent 2D Gaussian functional form, and accounting for the correlation between the intensity and the speed of the parent coronal mass ejection (CME), and the magnetic field line connection angle. The CME measurements used are from the SpaceWeather Database Of Notifications, Knowledge, Information (DONKI). The model performance, including its extrapolations to lower/higher energies, is tested by comparing with the spectra of 20 SEP events not used to derive the model parameters. Despite the simplicity of the model, the observed and predicted event-integrated and peak intensities at Earth and at the STEREO spacecraft for these events show remarkable agreement, both in the spectral shapes and their absolute values.

Table 1. List of CMEs associated with the SEP events analyzed in this work. (2010-2014)

Table 4. List of CMEs associated with the SEP events used for testing the empirical model (2011-2017)

Flux Variations in Lines of Solar EUV Radiation Beyond Flares in Cycle 24

E.A. **Bruevich**, G.V. Yakunina

Geomagnetizm and Aeronomy **2019**

https://arxiv.org/pdf/1912.10736.pdf

Studies in the extreme ultraviolet (EUV) and X-ray ranges of the solar spectrum are important due to the active role of radiation of these ranges in the formation of the Earth's ionosphere. Photons of the EUV range are completely absorbed in the upper layers of the Earth's atmosphere and induce the excitation, dissociation, and ionization of its different components and, finally, the atmospheric heating. From the archive data of the EUV Variability Experiment of the Solar Dynamics Observatory (SDO/EVE), we formed series of diurnal values of the background fluxes radiated beyond flares in the EUV lines HeII (30.4 nm), HeI (58.4 nm), CIII (97.7 nm), and FeXVIII (9.4 nm) in cycle 24 (from 2010 to 2017). These fluxes are compared to the corresponding values of the radio flux F10.7 at a wavelength of 10.7 cm and the background radiation flux F0.1-0.8 in the X-ray range between 0.1 and 0.8 nm measured onboard the GOES-15 satellite of the Geostationary Operational Environmental Satellite system. Comparative analysis has shown that the solar radiation in individual lines of the EUV range and the fluxes F10.7 and F0.1-0.8 are closely interrelated.

Thermosphere modeling capabilities assessment: geomagnetic storms

Sean **Bruinsma**1*, Claude Boniface1, Eric K. Sutton2 and Mariangel Fedrizzi3

J. Space Weather Space Clim. **2021**, 11, 12

https://www.swsc-journal.org/articles/swsc/pdf/2021/01/swsc200061.pdf
The specification and prediction of density fluctuations in the thermosphere, especially during geomagnetic storms, is a key challenge for space weather observations and modeling. It is of great operational importance for tracking objects orbiting in near-Earth space. For low-Earth orbit, variations in neutral density represent the most important uncertainty for propagation and prediction of satellite orbits. An international conference in 2018 conducted under the auspices of the NASA Community Coordinated Modeling Center (CCMC) included a workshop on neutral density modeling, using both empirical and numerical methods, and resulted in the organization of an initial effort of model comparison and evaluation. Here, we present an updated metric for model assessment under geomagnetic storm conditions by dividing a storm in four phases with respect to the time of minimum Dst and then calculating the mean density ratios and standard deviations and correlations. Comparisons between three empirical (NRLMSISE-00, JB2008 and DTM2013) and two first-principles models (TIE-GCM and CTIPe) and neutral density data sets that include measurements by the CHAMP, GRACE, and GOCE satellites for 13 storms are presented. The models all show reduced performance during storms, notably much increased standard deviations, but DTM2013, JB2008 and CTIPe did not on average reveal a significant bias in the four phases of our metric. DTM2013 and TIE-GCM driven with the Weimer model achieved the best results taking the entire storm event into account, while NRLMSISE-00 systematically and significantly underestimates the storm densities. Numerical models are still catching up to empirical methods on a statistical basis, but as their drivers become more accurate and they become available at higher resolutions, they will surpass them in the foreseeable future. **19-22 Nov 2003, 17-20 Jan 2005, 21-24 Jan 2005, 7-10 May 2005, 14-17 May 2005, 29 May-2 Jun 2005, 9-12 Jul 2005, 23-26 Aug 2005, 9-12 Sep 2005, 14-17 Dec 2006, 8-11 Mar 2012, 16-19 Mar 2013, 31 May-3 Jun 2013**
Table 3. Selected storm intervals 2003-2013

Space Weather Modeling Capabilities Assessment: Neutral Density for Orbit Determination at low Earth orbit

S. **Bruinsma**, E. Sutton, S. C. Solomon, T. Fuller-Rowell, M. Fedrizzi
Space Weather **2018** **Volume16, Issue11** Pages 1806-1816
hub.tw/10.1029/2018SW002027

The specification and prediction of density changes in the thermosphere is a key challenge for space weather observations and modeling, because it is one result of complex interactions between the Sun and the terrestrial atmosphere and also because it is of operational importance for tracking objects orbiting in near-Earth space. For low Earth orbit, neutral density variation is the most important uncertainty for propagation and prediction of orbital elements. A recent international conference conducted under the auspices of the National Aeronautics and Space Administration Community Coordinated Modeling Center included a workshop on neutral density modeling, using both empirical and numerical methods, and resulted in organization of an initial effort in model comparison and evaluation. Here we report on the exploitable density data sets available, the selected years and storm events, and the metrics for complete model assessment. Comparisons between five models (three empirical and two numerical) and neutral density data sets that include measurements by the CHAMP, GRACE, and GOCE satellites are presented as examples of the assessment procedure that will be implemented at Community Coordinated Modeling Center. The models in general performed reasonably well, although seasonal errors sometimes are present, and impulsive geomagnetic storm events remain challenging. Numerical models are still catching up to empirical methods on a statistical basis, but hold great potential for describing these short-term variations.

Space Weather Observations during September 2017 with CALET on the International Space Station

A. **Bruno**∗,1 , G. A. de Nolfo1 , A. W. Ficklin2 , T. G. Guzik2 and N. Cannady3
36th International cosmic-ray Conference -ICRC2019- July 24th - August 1st, **2019** Madison, WI, U.S.A
https://pos.sissa.it/358/1063/pdf

A period of extreme solar activity was observed in early September 2017, during the decaying phase of solar cycle 24. A large number of bright eruptions were registered, including a X9.3 flare on **6 September** and a X8.2 flare on **10 September**, the two strongest soft X-ray flares in almost 11 years. Both were associated with fast Coronal Mass Ejections (CMEs) and produced Solar Energetic Particle (SEP) events measured by several spacecraft. In particular, the second event was energetic enough to induce a Ground Level Enhancement (GLE) detected by the worldwide neutron monitor network, the second GLE of solar cycle 24. In this work we present a preliminary analysis of the September 2017 SEP events made with the CALorimetric Electron Telescope (CALET) onboard the International Space Station (ISS). We also investigate the relativistic electron precipitation (REP) events associated with the geomagnetic storms occurring in the same period. Data are compared with those of other space- and ground-based detectors.

R2O2R Improvements Identified by United States Space Weather Forecasters

E.C. **Bulter** , J.M. Keller
Space Weather **Volume19, Issue6** e2021SW002739 **2021**

https://doi.org/10.1029/2021SW002739
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021SW002739
A communication deficit exists between the space weather research and forecast communities in the research-to-operations-to-research (R2O2R) pipeline. No formal, citable space exists for forecasters to communicate needs and lessons learned to the research community (O2R). This deficit was termed the 'valleys of death and lost opportunities' (NRC, 2003, https://doi.org/10.17226/10658) and has resulted in advancements taking up to 20 years or more to become forecast operational. To provide this communication space, we surveyed a group of US civilian space weather forecasters on their needed improvements, use of available resources, and interactions with researchers, via a combination of questionnaire and focus group discussions. Nineteen needed improvements were identified, clustering into four categories: Scientific Understanding, Access to Data, Forecast Office Tools, and Instrumentation. Participants appeared to prefer resources with a robust data stream of high resolution and high time cadence data which suffers few technical issues. Participants want to be included in tool development more often and earlier in the process as they felt they were "seldom listened to when it comes to what [they] actually need."

Space Weather: From Solar Origins to Risks and Hazards Evolving in Time **Review**

Natalia **Buzulukova** (1 and 2), Bruce Tsurutani (3)
Front. Astron. Space Sci., **2022**
https://arxiv.org/ftp/arxiv/papers/2212/2212.11504.pdf **File**

Space Weather is the portion of space physics that has a direct effect on humankind. Space Weather is an old branch of space physics that originates back to 1808 with the publication of a paper by the great naturalist Alexander von Humboldt (von Humboldt, 1808). Space Weather is currently experiencing explosive growth, because its effects on human technologies have become more and more diverse. Space Weather is due to the variability of solar processes that cause interplanetary, magnetospheric, ionospheric, atmospheric and ground level effects. Space Weather can at times have strong impacts on technological systems and human health. The threats and risks are not hypothetical, and in the event of extreme Space Weather events the consequences could be quite severe for humankind. The purpose of the review is to give a brief overall view of the full chain of physical processes responsible for Space Weather risks and hazards, tracing them from solar origins to effects and impacts in interplanetary space, in the Earth's magnetosphere and ionosphere and at the ground. The paper shows that the risks associated with Space Weather have not been constant over time; they have evolved as our society becomes more and more technologically advanced. The paper begins with a brief introduction to the Carrington event. Next, the descriptions of the strongest known Space Weather processes are reviewed. The concepts of geomagnetic storms and substorms are briefly introduced. The main effects/impacts of Space Weather are also considered, including geomagnetically induced currents (GICs) which are thought to cause power outages. The effects of radiation on avionics and human health, ionospheric effects and impacts, and thermosphere effects and satellite drag will also be discussed. Finally, we will discuss the current challenges of Space Weather forecasting and examine some of the worst-case scenarios.

Extreme Events in Geospace

Origins, Predictability, and Consequences **Book**

Editor: Natalia **Buzulukova**, Elsevier, **2018**, 798 p. **File**
Site https://www.sciencedirect.com/science/article/pii/B9780128127001099921
Download PDF --> Download full book

Chapter 10 - Geomagnetic Storms: First-Principles Models for Extreme Geospace Environment **Review**

Natalia **Buzulukova***†Mei-ChingFok*AlexGlocer*ColinKomar*‡Suk-BinKang*StevenMartin*§Chigomezyo M.Ngwira*‡GuanLe*
In: Extreme Events in Geospace Origins, Predictability, and Consequences **2018**, Pages 231-258
http://sci-hub.tw/10.1016/B978-0-12-812700-1.00010-8

Many space weather effects intensify during geomagnetic storms potentially impacting Earth-based and spaceborne technological systems. In this chapter, we concentrate on geomagnetic storms' effects in the magnetosphere and provide descriptions of currently available 3D global modeling tools designed to reproduce the near-Earth space environment during geomagnetic storms. The outputs of these models could be used as inputs for ionosphere/thermosphere models (2D maps of ionospheric electric fields and precipitation), geomagnetically induced current models (geomagnetic variations on the Earth's surface), or environment models for spacecraft charging (ring current or radiation belt electron fluxes at spacecraft locations). We briefly review previously published results on modeling of large/extreme geomagnetic storms. We also provide an example simulation of the **June 22–23, 2015** magnetic storm with minimum Dst = −204 nT, showing the distribution of pressure and current density within the magnetosphere, provide comparisons with spacecraft measurements, and present a data-model comparison of modeled magnetograms with ground-based observations. We analyze sources of observed dB/dt variations, try to identify the responsible magnetospheric processes, and emphasize the role of the ring current at low latitudes. We also discuss challenges for the future improvement of two-way coupled models.

An abridged history of federal involvement in space weather forecasting **Review**

Becaja **Caldwell**, Eoin McCarron, Seth Jonas

Space Weather Volume 15, Issue 10 October **2017** Pages 1222–1237

Public awareness of space weather and its adverse effects on critical infrastructure systems, services, and technologies (e.g., the electric grid, telecommunications, and satellites) has grown through recent media coverage and scientific research. However, federal interest and involvement in space weather dates back to the decades between World War I and World War II when the National Bureau of Standards led efforts to observe, forecast, and provide warnings of space weather events that could interfere with high-frequency radio transmissions. The efforts to observe and predict space weather continued through the 1960s during the rise of the Cold War and into the present with U.S. government efforts to prepare the nation for space weather events. This paper provides a brief overview of the history of federal involvement in space weather forecasting from World War II, through the Apollo Program, and into the present.

Solar cycle variation in radar meteor rates

M D **Campbell-Brown**

Monthly Notices of the Royal Astronomical Society, Volume 485, Issue 3, May **2019**, Pages 4446–4453

sci-hub.se/10.1093/mnras/stz697

16 yr of meteor radar data from the Canadian Meteor Orbit Radar (CMOR) were used to investigate the link between observed meteor rates and both solar and geomagnetic activity. Meteor rates were corrected for transmitter power and receiver noise, and seasonal effects were removed. A strong negative correlation is seen between solar activity, as measured with the 10.7 cm flux, and observed meteor rates. This lends support to the idea that heating in the atmosphere at times of elevated solar activity changes the scale height and therefore the length and maximum brightness of meteors; a larger scale height near solar maximum leads to longer, fainter meteors and therefore lower rates. A weaker negative correlation was observed with geomagnetic activity as measured with the K index; this correlation was still present when solar activity effects were removed. Meteor activity at solar maximum is as much as 30 per cent lower than at solar minimum, strictly due to observing biases; geomagnetic activity usually affects meteor rates by less than 10 per cent.

ML-Helio: An Emerging Community at the Intersection Between Heliophysics and Machine Learning

Enrico **Camporeale**1 and The Scientific Organizing Committee of ML-Helio

Journal of Geophysical Research: Space Physics, 125, #2, e2019JA027502, **2020**

https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2019JA027502

The advancements and breakthroughs achieved in the last 5–10 years in Artificial Intelligence and machine learning (ML) have not gone unnoticed in the scientific community. The body of literature that borrows techniques from ML has steadily grown in all fields of physics. Space physics is particularly well posed to exploit ML due to the large amount of (often under scrutinized) data accumulated over the last few decades. Indeed, ML techniques can offer insights into the data that might enhance our understanding of physical mechanisms. Many of the pioneering studies on the use of ML in Space Physics have been led by several individuals who have independently taken the burden of moving out of their comfort zone to climb the steep slope of learning new jargon, new methodologies, and new coding skills. Such early adopters have recently convened in Amsterdam for the first conference on machine learning in heliophysics. The conference has laid the foundation for a new emerging community, and this commentary summarizes the discussions and steps taken to make such community flourish.

See https://ml-helio.github.io

The Challenge of Machine Learning in Space Weather: Nowcasting and Forecasting **Review**

E. **Camporeale**

Space Weather Volume17, Issue8 Pages 1166-1207 **2019**

sci-hub.se/10.1029/2018SW002061

The numerous recent breakthroughs in machine learning make imperative to carefully ponder how the scientific community can benefit from a technology that, although not necessarily new, is today living its golden age. This Grand Challenge review paper is focused on the present and future role of machine learning in Space Weather. The purpose is twofold. On one hand, we will discuss previous works that use machine learning for Space Weather forecasting, focusing in particular on the few areas that have seen most activity: the forecasting of geomagnetic indices, of relativistic electrons at geosynchronous orbits, of solar flares occurrence, of coronal mass ejection propagation time, and of solar wind speed. On the other hand, this paper serves as a gentle introduction to the field of machine learning tailored to the Space Weather community and as a pointer to a number of open challenges that we believe the community should undertake in the next decade. The recurring themes throughout the review are the need to shift our forecasting paradigm to a probabilistic approach focused on the reliable assessment of uncertainties, and the combination of physics-based and machine learning approaches, known as gray-box.

On the Generation of Probabilistic Forecasts From Deterministic Models

E. **Camporeale**, X. Chu , O. V. Agapitov , J. Bortnik
SpaceWeather Volume17, Issue3 Pages 455-475 **2019**
sci-hub.si/10.1029/2018SW002026

Most of the methods that produce space weather forecasts are based on deterministic models. In order to generate a probabilistic forecast, a model needs to be run several times sampling the input parameter space, in order to generate an ensemble from which the distribution of outputs can be inferred. However, ensemble simulations are costly and often preclude the possibility of real-time forecasting. We introduce a simple and robust method to generate uncertainties from deterministic models, that does not require ensemble simulations. The method is based on the simple consideration that a probabilistic forecast needs to be both accurate and well calibrated (reliable). We argue that these two requirements are equally important, and we introduce the Accuracy-Reliability cost function that quantitatively measures the trade-off between accuracy and reliability. We then define the optimal uncertainties as the standard deviation of the Gaussian distribution that minimizes the cost function. We demonstrate that this simple strategy, implemented here by means of a deep neural network, produces accurate and well-calibrated forecasts, showing examples both on synthetic and real-world space weather data.

Space weather in the machine learning era,

Camporeale, E., S. Wing, and J. Johnson
(**2018**), Eos, 99, https://doi.org/10.1029/2018EO101897
https://eos.org/meeting-reports/space-weather-in-the-machine-learning-era?utm_source=eos&utm_medium=email&utm_campaign=EosBuzz071318
Workshop materials are available here. https://event.cwi.nl/spaceweather2017/index.html

Space Weather in the Machine Learning Era: A Multidisciplinary Approach

E. **Camporeale**, S. Wing, J. Johnson, C. M. Jackman, R. McGranaghan
Space Weather Volume 16, Issue 1 January **2018** Pages 2–4
http://sci-hub.tw/10.1002/2017SW001775

The workshop entitled Space Weather: A Multidisciplinary Approach took place at the Lorentz Center, University of Leiden, Netherlands, on 25–29 September 2017. The aim of this workshop was to bring together members of the Space Weather, Mathematics, Statistics, and Computer Science communities to address the use of advanced techniques such as Machine Learning, Information Theory, and Deep Learning, to better understand the Sun-Earth system and to improve space weather forecasting. Although individual efforts have been made toward this goal, the community consensus is that establishing interdisciplinary collaborations is the most promising strategy for fully utilizing the potential of these advanced techniques in solving Space Weather-related problems.

Space Weather in the Machine Learning Era: A Multidisciplinary Approach

Camporeale, E., Wing, S., Johnson, J., Jackman, C. M., & McGranaghan, R.
Space Weather Quarterly Vol. 15, Issue 1, **2018**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/swq.17

The authors reflect on the Space Weather: A Multidisciplinary Approach workshop that took place at the Lorentz Center, University of Leiden, Netherlands, on 25–29 September 2017. The workshop participants agreed that machine learning, information theory, deep learning techniques, and methods have the potential to help solve important open questions in Space Weather.

Extreme Space Weather: Impacts on Engineered Systems and Infrastructures, **Reiew**

Cannon, P., Angling, M., Barclay, L., Curry, C., Dyer, C., Edwards, R., Greene, G., Hapgood, M., Horne, R., Jackson, D., Mitchell, C., Owen, J., Richards, A., Rogers, C., Ryden, K., Saunders, S., Sweeting, M., Tanner, R., Thomson, A., Underwood, C.:
2016, 70. ISBN 1903496969.
www.raeng.org.uk/spaceweather.

Radio observatories and instrumentation used in space weather science and operations

Eoin P. **Carley**1,2,*, Carla Baldovin3 , Pieter Benthem3 , Mario M. Bisi4 , Richard A. Fallows3 , Peter T. Gallagher2,1, Michael Olberg5 , Hanna Rothkaehl6 , Rene Vermeulen3 , Nicole Vilmer7,8, David Barnes4 , the LOFAR4SW Consortium3
J. Space Weather Space Clim. **2020**, 10, 7 **File** **Review**
https://www.swsc-journal.org/articles/swsc/pdf/2020/01/swsc190064.pdf
The low frequency array (LOFAR) is a phased array interferometer currently consisting of 13 international stations across Europe and 38 stations surrounding a central hub in the Netherlands. The instrument operates in the frequency range of ~10–240 MHz and is used for a variety of astrophysical science cases. While it is not heliophysics or space weather dedicated, a new project entitled "LOFAR for Space Weather" (LOFAR4SW) aims at designing a system upgrade to allow the entire array to observe the Sun, heliosphere, Earth's ionosphere, and Jupiter throughout its observing window. This will allow the instrument to operate as a space weather observing platform, facilitating both space weather science and operations. Part of this design study aims to survey the existing space weather infrastructure operating at radio frequencies and show how LOFAR4SW can advance the current state-of-the-art in this field. In this paper, we survey radio instrumentation and facilities that currently operate in space weather science and/or operations, including instruments involved in solar, heliospheric, and ionospheric studies. We furthermore include an overview of the major space weather service providers in operation today and the current state-of-the-art in the radio data they use and provide routinely. The aim is to compare LOFAR4SW to the existing radio research infrastructure in space weather and show how it may advance both space weather science and operations in the radio domain in the near future.
Хороший справочник

Space Weather in the Popular Media, and the Opportunities the Upcoming Solar Maximum Brings

Brett A. **Carter**, Noé Lugaz, Steven K. Morley, Jennifer Gannon, Shasha Zou, Huixin Liu
Space Weather Volume21, Issue12 December **2023** e2023SW003819
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2023SW003819
https://doi.org/10.1029/2023SW003819
The media interest/coverage of space weather has been increasing as we approach solar maximum and the private space industry has grown significantly since the last significant solar maximum in 2000–2002. It is not uncommon for space weather media coverage to use hyperbole with frequent references to the infamous "Carrington event." The implications of associating each of the many upcoming moderate-to-severe storms with the Carrington event are discussed, and we encourage the curbing of hyperbole whenever possible. While there is an excellent but small cohort of space weather researchers actively engaging with the media, we urge more (particularly early-to-mid career) to take advantage of media training resources and to join in. We also call for these efforts to be broadly supported by peers and institutions for the benefit of space weather as a discipline.

RMIT University's practical space weather prediction laboratory

Brett A. **Carter**, et al.
J. Space Weather Space Clim. **2022**, 12, 28
https://www.swsc-journal.org/articles/swsc/full_html/2022/01/swsc210070/swsc210070.html
https://doi.org/10.1051/swsc/2022025
https://www.swsc-journal.org/articles/swsc/pdf/2022/01/swsc210070.pdf
Space weather is a key component in the daily operation of many technological systems and applications, including large-scale power grids, high-frequency radio systems, and satellite systems. As the international space sector continues to boom, accessible space weather products, tools and education are increasingly important to ensure that space actors (both old and new) are equipped with the knowledge of how space weather influences their activities and applications. At RMIT University, the initiative was taken to develop a Space Weather Prediction Laboratory exercise for students as part of its new offering of a Bachelor's Degree in Space Science in 2020. This new Space Weather Prediction Lab exercise is offered as part of an undergraduate course on "Space Exploration", which has a diverse student in-take, including students with no background in physics; a key detail in the design of the Lab. The aims of the Space Weather Prediction Lab were to: (1) provide a short and intense introduction to the near-Earth space environment and its impact on various human technologies; (2) give students "hands-on" training in data analysis, interpretation and communication; and (3) create an immersive space science experience for students that encourages learning, scientific transparency and teamwork. The format of the lab that was developed can be easily scaled in difficulty to suit the students' technical level, either by including more/less space weather datasets in the analysis or by analyzing more/less complicated space weather events. The details of the Space Weather Prediction Lab developed and taught at RMIT in 2020, in both face-to-face and online formats, are presented. **4-9 Sep 2017**

Solar flare caused increased oxygen loss from Mars's atmosphere,

Cartier, K. M. S.
(**2018**), Eos, 99,https://doi.org/10.1029/2018EO100455. Published on 04 June 2018.

https://eos.org/articles/solar-flare-caused-increased-oxygen-loss-from-marss-atmosphere?utm_source=eos&utm_medium=email&utm_campaign=EosBuzz060818

Small Satellite Mission Concepts for Space Weather Research and as Pathfinders for Operations

Amir **Caspi**, M. Barthelemy, C. D. Bussy-Virat, I. J. Cohen, C. E. DeForest, D. R. Jackson, A. Vourlidas, T. Nieves-Chinchilla

Space Weather **Volume20, Issue2** e2020SW002554 **2022**
https://arxiv.org/ftp/arxiv/papers/2201/2201.07426.pdf
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020SW002554
https://doi.org/10.1029/2020SW002554

Recent advances in miniaturization and commercial availability of critical satellite subsystems and detector technology have made small satellites (SmallSats, including CubeSats) an attractive, low-cost potential solution for space weather research and operational needs. Motivated by the 1st International Workshop on SmallSats for Space Weather Research and Forecasting, held in Washington, DC on 1-4 August 2017, we discuss the need for advanced space weather measurement capabilities, driven by analyses from the World Meteorological Organization (WMO), and how SmallSats can efficiently fill these measurement gaps. We present some current, recent missions and proposed/upcoming mission concepts using SmallSats that enhance space weather research and provide prototyping pathways for future operational applications; how they relate to the WMO requirements; and what challenges remain to be overcome to meet the WMO goals and operational needs in the future. With additional investment from cognizant funding agencies worldwide, SmallSats -- including standalone missions and constellations -- could significantly enhance space weather research and, eventually, operations, by reducing costs and enabling new measurements not feasible from traditional, large, monolithic missions.

Space physics and policy for contemporary society **Review**

P. A. **Cassak**1 , A. G. Emslie2, A. J. Halford3 , D. N. Baker4 , H. E. Spence5 ,
S. K. Avery6,7, and L. A. Fisk8

JGR **2017**
http://onlinelibrary.wiley.com/doi/10.1002/2017JA024219/pdf

Space physics is the study of Earth's home in space. Elements of space physics include how the Sun works from its interior to its atmosphere, the environment between the Sun and planets out to the interstellar medium, and the physics of the magnetic barriers surrounding Earth and other planets. Space physics is highly relevant to society. Space weather, with its goal of predicting how Earth's technological infrastructure responds to activity on the Sun, is an oft-cited example, but there are many more. Space physics has important impacts in formulating public policy.

Solar storms and submarine internet cables

Jorge C. **Castellanos**, Jo Conroy, Valey Kamalov, Urs Hölzle

2022
https://arxiv.org/ftp/arxiv/papers/2211/2211.07850.pdf

Coronal mass ejections (CMEs) can trigger geomagnetic storms and induce geoelectric currents that degrade the performance of terrestrial power grid operations; in particular, CMEs are known for causing large-scale outages in electrical grids. Submarine internet cables are powered through copper conductors spanning thousands of kilometers and are vulnerable to damage from CMEs, raising the possibility of a large-scale and long-lived internet outage. To better understand the magnitude of these risks, we monitor voltage changes in the cable power supply of four different transoceanic cables during time periods of high solar activity. We find a strong correlation between the strength of the high-frequency geomagnetic field at the landing sites of the systems and the line voltage change. We also uncover that these two quantities exhibit a near-linear power law scaling behavior that allows us to estimate the effects of once-in-a-century CME events. Our findings reveal that long-haul submarine cables, regardless of their length and orientation, will not be damaged during a solar superstorm, even one as large as the 1859 Carrington event.

Effect of intense December 2006 solar radio bursts on GPS receivers

Cerruti, Alessandro P.; Kintner, Paul M., Jr.; Gary, Dale E.; Mannucci, Anthony J.; Meyer, Robert F.; Doherty, Patricia; Coster, Anthea J.

Space Weather, Vol. 6, No. 10, S10D07
http://dx.doi.org/10.1029/2007SW000375
http://onlinelibrary.wiley.com/doi/10.1029/2007SW000375/pdf
http://sci-hub.tw/10.1029/2007SW000375
Solar radio bursts during December 2006 were sufficiently intense to be measurable with GPS receivers. The strongest event occurred on 6 December 2006 and affected the operation of many GPS receivers. This event exceeded 1,000,000 solar flux unit and was about 10 times larger than any previously reported event. The strength of the event was especially surprising since the solar radio bursts occurred near solar minimum. The strongest periods of solar radio burst activity lasted a few minutes to a few tens of minutes and, in some cases, exhibited large intensity differences between L1 (1575.42 MHz) and L2 (1227.60 MHz). Civilian dual frequency GPS receivers were the most severely affected, and these events suggest that continuous, precise positioning services should account for solar radio bursts in their operational plans. This investigation raises the possibility of even more intense solar radio bursts during the next solar maximum that will significantly impact the operation of GPS receivers.

Ionospheric response to Strong Geomagnetic Storms during 2000-2005: An IMF clock angle perspective

Sumanjit **Chakraborty**, Sarbani Ray, Abhirup Datta, Ashik Paul
Radio Science **2020**
https://arxiv.org/pdf/2008.06765.pdf
This paper presents the equatorial ionospheric response to eleven strong-to-severe geomagnetic storms that occurred during the period 2000-2005, the declining phase of the solar cycle 23. The analysis has been performed using the global ion density plots of Defense Meteorological Satellite Program (DMSP). Observations show that for about 91% of the cases, post-sunset equatorial irregularities occurred within 3h from the time of northward to southward transition of the Interplanetary Magnetic Field (IMF) clock angle, thus bringing out the importance of the role played by IMF By in the process of Prompt Penetration of Electric Field (PPEF) in addition to the IMF Bz. This is an improvement from the previously reported (Ray et al.,2015) 4h window of ESF generation from the southward IMF Bz crossing -10 nT. **April 05-07, 2000, May 29-31, 2005**

Table 1. Minimum Dst values with the corresponding Day of Year and Date (DOY(DD)) of minimum for the severe storms analyzed during 2000-2005

A Study of SuperDARN Response to Co-occurring Space Weather Phenomena

S. **Chakraborty**, J.B.H. Baker, J.M. Ruohoniemi, B. Kunduri, N. Nishitani, S.G. Shepherd
Space Weather 17, No. 9, 1351–1363 **2019**
sci-hub.se/10.1029/2019SW002179
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019SW002179

Solar Ultraviolet Irradiance Observations of the Solar Flares During the Intense September 2017 Storm Period

P. C. **Chamberlin**, T. N. Woods, L. Didkovsky, F. G. Eparvier, A. R. Jones, J. L. Machol, J. P. Mason, M. Snow, E. M. B. Thiemann, R. A. Viereck, D. L. Woodraska
Space Weather Volume16, Issue10 Pages 1470-1487 **2018**
http://sci-hub.tw/https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018SW001866
sci-hub.tw/10.1029/2018SW001866
A large outburst of flares occurred between 4–10 September 2017 when new magnetic flux emerged into and strengthened an existing active region, National Oceanic and Atmospheric Administration Region 12673. This intense solar storm period included X9.3 (6 September) and X8.2 (10 September) flares, the largest flares that have occurred during Solar Cycle 24, as well as 39 M-class flares and three additional X-class flares. Another X-class flare from this active region was observed on the farside of the Sun from Mars Atmosphere and Volatile EvolutioN prior to the September events, along with other large M-class flares, showing the potential for how farside irradiance monitoring can improve flare prediction at Earth for 1- to 13-day forecasts. This September 2017 flare period is similar to other famous storm periods such as the 18 October to 5 November 2003 Halloween storm that produced 14 X-class flares and 137 M-class flares and the 6–10 September 2005 period that had 11 X-class and 68 M-class flares. All of these storm periods occurred in the declining phase of the solar cycle when solar activity had decreased significantly from solar maximum levels. This paper focuses on a number of solar irradiance observations at ultraviolet (0–190 nm) wavelengths during the September 2017 storm period and the advantages that an ensemble of measurements and models have for studying solar flares.

Space Radiation: The Number One Risk to Astronaut Health beyond Low Earth Orbit

Jeffery C. **Chancellor** 1,2 ,Graham B. I. Scott 1,3 andJeffrey P. Sutton 1,4,*

Life **2014**, 4(3), 491-510; https://doi.org/10.3390/life4030491
http://www.mdpi.com/2075-1729/4/3/491/pdf

Projecting a vision for space radiobiological research necessitates understanding the nature of the space radiation environment and how radiation risks influence mission planning, timelines and operational decisions. Exposure to space radiation increases the risks of astronauts developing cancer, experiencing central nervous system (CNS) decrements, exhibiting degenerative tissue effects or developing acute radiation syndrome. One or more of these deleterious health effects could develop during future multi-year space exploration missions beyond low Earth orbit (LEO). Shielding is an effective countermeasure against solar particle events (SPEs), but is ineffective in protecting crew members from the biological impacts of fast moving, highly-charged galactic cosmic radiation (GCR) nuclei. Astronauts traveling on a protracted voyage to Mars may be exposed to SPE radiation events, overlaid on a more predictable flux of GCR. Therefore, ground-based research studies employing model organisms seeking to accurately mimic the biological effects of the space radiation environment must concatenate exposures to both proton and heavy ion sources. New techniques in genomics, proteomics, metabolomics and other "omics" areas should also be intelligently employed and correlated with phenotypic observations. This approach will more precisely elucidate the effects of space radiation on human physiology and aid in developing personalized radiological countermeasures for astronauts.

PRESTO – Predictability of the Variable Solar-Terrestrial Coupling
Pillar 2: Space weather and Earth's atmosphere
L. C. **Chang**1, D. Pallamraju2 and N. M. Pedatella3
SCOSTEP__PRESTO Newsletter **2020 File**

Reproducible Aspects of the Climate of Space Weather Over the Last Five Solar Cycles
S. C. **Chapman**, N. W. Watkins, E. Tindale
Space Weather
Volume16, Issue8 August **2018** Pages 1128-1142
https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2018SW001884

Each solar maximum interval has a different duration and peak activity level, which is reflected in the behavior of key physical variables that characterize solar and solar wind driving and magnetospheric response. The variation in the statistical distributions of the F10.7 index of solar coronal radio emissions, the dynamic pressure PDyn and effective convection electric field Ey in the solar wind observed in situ upstream of Earth, the ring current index DST, and the high-latitude auroral activity index AE are tracked across the last five solar maxima. For each physical variable we find that the distribution tail (the exceedences above a threshold) can be rescaled onto a single master distribution using the mean and variance specific to each solar maximum interval. We provide generalized Pareto distribution fits to the different master distributions for each of the variables. If the mean and variance of the large-to-extreme observations can be predicted for a given solar maximum, then their full distribution is known.

Identifying Solar Flare Precursors Using Time Series of SDO/HMI Images and SHARP Parameters
Yang **Chen**, Ward B. Manchester, Alfred O. Hero, Gabor Toth, Benoit DuFumier, Tian Zhou, Xiantong Wang, Haonan Zhu, Zeyu Sun, Tamas I. Gombosi
Space Weather **2019**
https://arxiv.org/pdf/1904.00125.pdf

We present several methods towards construction of precursors, which show great promise towards early predictions, of solar flare events in this paper. A data pre-processing pipeline is built to extract useful data from multiple sources (Geostationary Operational Environmental Satellites (GOES) and Solar Dynamics Observatory (SDO)/Helioseismic and Magnetic Imager (HMI) to prepare inputs for machine learning algorithms. Two classification models are presented: classification of flares from quiet times for active regions and classification of strong versus weak flare events. We adopt deep learning algorithms to capture both the spatial and temporal information from HMI magnetogram data. Effective feature extraction and feature selection with raw magnetogram data using deep learning and statistical algorithms enable us to train classification models to achieve almost as good performance as using active region parameters provided in HMI/Space-Weather HMI-Active Region Patch (SHARP) data files. The results show great promise towards accurate, reliable, and timely predictions of solar flare events. The use of Atmospheric Imaging Assembly (AIA) data will be the topic of future studies.

Solar Eruptions, Forbush Decreases and Geomagnetic Disturbances from Outstanding Active Region 12673
I.M. **Chertok**, A.V. Belov, A.A. Abunin
Space Weather **2018**

https://arxiv.org/ftp/arxiv/papers/1809/1809.07961.pdf
Based on our tool for the early diagnostics of solar eruption geoeffectiveness (EDSEG tool; Chertok et al., 2013, 2015, 2017), we have analyzed space weather disturbances that occurred in early September 2017. Two flares, SOL2017-09-04T20:33 (M5.5) and SOL2017-09-06T12:02 (X9.3), accompanied by Earth-directed halo coronal mass ejections (CMEs) were found to be geoeffective. We extracted the associated EUV dimmings and arcades and calculated their total unsigned magnetic flux. This calculation allowed us to estimate the possible scales of the Forbush decreases (FDs) and geomagnetic storms (GMSs) in the range from moderate to strong, and they are close to the observed scales. More precisely, after the first eruption, an FD approximately equal to 2% and almost no GMS occurred because the Bz magnetic field component in front of the corresponding interplanetary CME (ICME) was northern. The stronger second eruption produced somewhat larger composite disturbances (FD ~ 9.3% and GMS with indexes Dst ~ -144 nT, Ap ~ 235) than expected (FD ~ 4.4%, Dst ~ -135 nT, Ap ~ 125) because the second ICME overtook the trailing part of the first ICME near Earth, and the resulting Bz component was more intense and southern. Both ICMEs arrived at Earth earlier than expected because they propagated in the high-speed solar wind emanated from an extended coronal hole adjacent to AR12673 along their entire path. Overall, the presented results provide further evidence that the EDSEG tool can be used for the earliest diagnostics of actual solar eruptions to forecast the scale of the corresponding geospace disturbances.

Geoeffectiveness of Stream Interaction Regions From 1995 to 2016

Yutian **Chi** Chenglong Shen Bingxian Luo Yuming Wang Mengjiao Xu

Space Weather 16?, 12, 1960-1971 **2018**

http://sci-hub.tw/10.1029/2018SW001894

Stream interaction regions (SIRs) are important sources of geomagnetic storms. In this work, we first extend the end time of the widely used SIR catalog developed by Jian et al. (2006, https://doi.org/10.1007/s11207-006-0132-3), which covered the period from 1995 to 2009, to the end of 2016. Based on this extended SIR catalog, the geoeffectiveness of SIRs is discussed in detail. It was found that 52% of the SIRs caused geomagnetic storms with Dstmin ≤−30 nT, but only 3% of them caused intense geomagnetic storms with Dstmin≤−100 nT. Furthermore, we found that 10 of the intense geomagnetic storms caused by SIRs were associated with complex structures due to interactions between SIRs and interplanetary coronal mass ejections (ICMEs). In such a structure, an ICME is embedded in the SIR and located between the slow and fast solar wind streams. In addition, we found that the geoeffectiveness of SIRs interacting with ICMEs is enhanced. The possibility of SIR-ICME interaction structures causing geomagnetic storms is markedly higher than that of isolated SIRs or isolated ICMEs. In particular, the geoeffectiveness of SIR-ICME interaction structures is similar to that of the Shock-ICME interaction structures, which have been demonstrated to be the main causes of geomagnetic storms.

Space weather in the EU's FP7 Space Theme
Preface to the special issue on "EU-FP7 funded space weather projects"

Paola **Chiarini**

J. Space Weather Space Clim. 3 (**2013**) E01

http://www.swsc-journal.org/articles/swsc/pdf/2013/01/swsc130049.pdf

Technological infrastructures in space and on ground provide services on which modern society and economies rely. Space weather related research is funded under the 7th Framework Programme for Research and Innovation (FP7) of the European Union in response to the need of protecting such critical infrastructures from the damage which could be caused by extreme space weather events. The calls for proposals published under the topic "Security of space assets from space weather events" of the FP7 Space Theme aimed to improve forecasts and predictions of disruptive space weather events as well as identify best practices to limit the impacts on space- and ground-based infrastructures and their data provision. Space weather related work was also funded under the topic "Exploitation of space science and exploration data", which aims to add value to space missions and Earth-based observations by contributing to the effective scientific exploitation of collected data. Since 2007 a total of 20 collaborative projects have been funded, covering a variety of physical phenomena associated with space weather, from ionospheric disturbances and scintillation, to geomagnetically induced currents at Earth's surface, to coronal mass ejections and solar energetic particles. This article provides an overview of the funded projects, touching upon some results and referring to specific websites for a more exhaustive description of the projects' outcomes.

Analysis of GEO spacecraft anomalies: Space weather relationships

Choi, Ho-Sung; Lee, Jaejin; Cho, Kyung-Suk; Kwak, Young-Sil; Cho, Il-Hyun; Park, Young-Deuk; Kim, Yeon-Han; Baker, Daniel N.; Reeves, Geoffrey D.; Lee, Dong-Kyu

Space Weather, Vol. 9, No. 6, S06001, **2011**

While numerous anomalies and failures of spacecraft have been reported since the beginning of the space age, space weather effects on modern spacecraft systems have been emphasized more and more with the increase of their complexity and capability. However, the relationship between space weather and commercial satellite anomalies has not been studied extensively. In this paper, we investigate the geostationary Earth orbit (GEO) satellite anomalies archived by Satellite News Digest during 1997–2009 in order to search for possible influences of space weather on the anomaly occurrences. We analyze spacecraft anomalies for the Kp index, local time, and season and then compare them with the tendencies of charged particles observed by Los Alamos National Laboratory (LANL) satellites. We obtain the following results: (1) there are good relationships between geomagnetic activity (as measured by the Kp index) and anomaly occurrences of the GEO satellites; (2) the satellite anomalies occurred mainly in the midnight to morning sector; and (3) the anomalies are found more frequently in spring and fall than summer and winter. While we cannot fully explain how space weather is involved in producing such anomalies, our analysis of LANL data shows that low-energy (<100 keV) electrons have similar behaviors with spacecraft anomalies and implies the spacecraft charging might dominantly contribute to the GEO spacecraft anomalies reported in Satellite News Digest.

Comment on "Analysis of GEO spacecraft anomalies: Space weather relationships" by Ho-Sung Choi et al.
Mazur, Joseph E.
Space Weather, Vol. 10, No. 3, S03003, **2012**
http://dx.doi.org/10.1029/2011SW000738

Reply to comment by Joseph E. Mazur and T. Paul O'Brien on "Analysis of GEO spacecraft anomalies: Space weather relationships"
Space Weather, Vol. 10, No. 3, S03004, 2012
http://dx.doi.org/10.1029/2012SW000765

Contemporary Space Weather Need: Going Beyond the Global Oscillation Network Group

Debi Prasad **Choudhary**

Space Weather Volume17, Issue3 Pages 375-378 **2019**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2018SW002097
https://doi.org/10.1029/2018SW002097
Space Weather Quarterly 16, issue 1, 31-33, **2019**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/swq.21

The article “The Global Oscillation Network Group (GONG) Facility—An Example of Research to Operations in Space Weather” by Frank Hill (https://doi.org/10.1029/2018SW002001) narrates how an instrument built for answering questions of basic research is playing a greater role in the field of space weather. In the past 25 years, the project has successfully produced fundamental results that have helped to fine tune stellar structure models and have resolved several outstanding problems in solar physics. It is also important to know the background coronal and solar wind environment in order to understand and adequately predict the transient events as this is the environment through which they propagate. The GONG magnetograms are useful as boundary conditions to construct the large-scale magnetic field structure of the heliosphere and at times to detect the change in longitudinal field due to the solar flares. In order to advance the space weather prediction tools, it is necessary to study the magnetic and thermodynamic properties of the source regions of the transient events. The rich information contained in the polarized spectra originating at these locations that is currently measured by the “Synoptic Optical Long-term Investigations of the Sun” instrument are most appropriate for this purpose. Although, GONG magnetograms have been, and continue to be, useful in understanding some aspects of space weather, there remains a need for new solar observing capabilities aimed at better understanding the “Transient Sun.” In this commentary, we describe the need for a GONG upgrade that will fully serve the Space Weather Community.

Developing the LDi and LCi geomagnetic indices, an example of application of the AULs framework

C. **Cid**, A. Guerrero, E. Saiz, A.J. Halford, A.C. Kellerman

Space Weather **2020**
sci-hub.se/10.1029/2019SW002171

The Application Usability Level (AULs) framework has been recently introduced as an efficient and effective way to track progress towards the needs of a user for a specific application. This paper is an example of how the AUL framework facilitates communication between the industry users of space weather research and researchers for developing a product. The products are two new geomagnetic indices fully approved for on-demand use: the LDi index, for nowcasting local geomagnetic disturbances, and the LCi index, as a proxy for the geomagnetically induced currents risk.

Is the F10.7cm – Sunspot Number relation linear and stable?

Frédéric **Clette***

J. Space Weather Space Clim. **2021**, 11, 2
https://doi.org/10.1051/swsc/2020071

Is the F10.7cm – Sunspot Number relation linear and stable? (swsc-journal.org)
The F10.7cm radio flux and the Sunspot Number are the most widely used long-term indices of solar activity. They are strongly correlated, which led to the publication of many proxy relations allowing to convert one index onto the other. However, those existing proxies show significant disagreements, in particular at low solar activity. Moreover, a temporal drift was recently found in the relative scale of those two solar indices. Our aim is to bring a global clarification of those many issues. We compute new polynomial regressions up to degree 4, in order to obtain a more accurate proxy over the whole range of solar activity. We also study the role of temporal averaging on the regression, and we investigate the issue of the all-quiet F10.7 background flux. Finally, we check for any change in the F10.7–Sunspot Number relation over the entire period 1947–2015. We find that, with a 4th-degree polynomial, we obtain a more accurate proxy relation than all previous published ones, and we derive a formula giving standard errors. The relation is different for daily, monthly and yearly mean values, and it proves to be fully linear for raw non-averaged daily data. By a simple two-component model for daily values, we show how temporal averaging leads to non-linear proxy relations. We also show that the quiet-Sun F10.7 background is not absolute and actually depends on the duration of the spotless periods. Finally, we find that the F10.7cm time series is inhomogeneous, with an abrupt 10.5% upward jump occurring between 1980 and 1981, and splitting the series in two stable intervals. Our new proxy relations bring a strong improvement and show the importance of temporal scale for choosing the appropriate proxy and the F10.7 quiet-Sun background level. From historical evidence, we conclude that the 1981 jump is most likely due to a unique change in the F10.7 scientific team and the data processing, and that the newly re-calibrated sunspot number (version 2) will probably provide the only possible reference to correct this inhomogeneity.

A Citizen Science Network for Measurements of Atmospheric Ionizing Radiation Levels

B. J. **Clewer** K. A. Ryden A. C. R. Dyer A. D. P. Hands D. R. Jackson

Space Weather Volume17, Issue6 Pages 877-893 **2019**
sci-hub.se/10.1029/2019SW002190
Space Weather Quarterly Volume 16, Issue 3 p. 5-19, **2019**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/swq.23

Historically, gathering data on atmospheric radiation levels during solar particle events has been difficult, as there is little or no time warning of events. Being able to accurately quantify radiation levels within the atmosphere during solar events is of significance to the aviation industry, as described in the International Civil Aviation Organization's (ICAO) Space Weather manual. Particularly during a large ground-level enhancement (GLE) where the ionizing dose to passengers and crew can exceed the recommended general public annual dose limits, set by the International Commission for Radiological Protection (Barlett, Beck, Bilski, Bottollier-Depois, & Lindborg, 2004, https://doi.org/10.1093/rpd/nch232), in a single flight. The Smart Atmospheric Ionizing RAdiation (SAIRA) Monitoring Network is a new system of handheld radiation detectors that can be carried on aircraft to monitor and record atmospheric radiation levels. The system operates via citizen science volunteers, who record radiation data as they travel for normal purposes. Over 30 flights have been conducted with volunteers to demonstrate that a citizen science network is possible. Volunteers have used a new Android application to record and upload data to a central server to form a database of flight measurements. The demonstration has shown that there is a willingness in public volunteers to use radiation detectors and engage in science outreach. A fully developed system will ideally provide the capability to quantify radiation levels during a solar particle event or ground-level enhancement and the data can be used by relevant organizations to minimize potential risks.

Geomagnetically induced currents during the 07–08 September 2017 disturbed period: a global perspective

Mark A. **Clilverd**, et al.

J. Space Weather Space Clim. **2021**, 11, 33
https://doi.org/10.1051/swsc/2021014
https://www.swsc-journal.org/articles/swsc/pdf/2021/01/swsc200090.pdf

Measurements from six longitudinally separated magnetic observatories, all located close to the 53° mid-latitude contour, are analysed. We focus on the large geomagnetic disturbance that occurred during **7 and 8 September 2017**. Combined with available geomagnetically induced current (GIC) data from two substations, each located near to a magnetic observatory, we investigate the magnetospheric drivers of the largest events. We analyse solar wind parameters combined with auroral electrojet indices to investigate the driving mechanisms. Six magnetic field disturbance events were observed at mid-latitudes with dH/dt > 60 nT/min. Co-located GIC measurements identified transformer currents >15 A during three of the events. The initial event was caused by a solar wind pressure pulse causing largest effects on the dayside, consistent with the rapid compression of the dayside geomagnetic field. Four of the events were caused by substorms. Variations in the Magnetic Local Time of the maximum effect of each substorm-driven event were apparent, with magnetic midnight, morning-side, and dusk-side events all occurring. The six events occurred over a period of almost 24 h, during which the solar wind remained elevated at >700 km s−1, indicating an extended time scale for potential GIC problems in electrical power networks following a sudden storm commencement. This work demonstrates the challenge of understanding the causes of ground-level magnetic field changes (and hence GIC magnitudes) for the global power industry. It also demonstrates the importance of magnetic local time and differing inner magnetospheric processes when considering the global hazard posed by GIC to power grids.

Long-Lasting Geomagnetically Induced Currents and Harmonic Distortion Observed in New Zealand During the 7–8 September 2017 Disturbed Period

Mark A. **Clilverd**, Craig J. Rodger, James B. Brundell, Michael Dalzell, Ian Martin, Daniel H. Mac Manus, Neil R. Thomson, Tanja Petersen, Yuki Obana

Space Weather Volume16, Issue6 June **2018** Pages 704-717
http://sci-hub.tw/10.1029/2018SW001822

Several periods of geomagnetically induced currents (GICs) were detected in the Halfway Bush substation in Dunedin, South Island, New Zealand, as a result of intense geomagnetic storm activity during 6 to 9 September 2017. Unprecedented data coverage from a unique combination of instrumentation is analyzed, that is, measurements of GIC on the single-phase bank transformer T4 located within the substation, nearby magnetic field perturbation measurements, very low frequency (VLF) wideband measurements detecting the presence of power system harmonics, and high-voltage harmonic distortion measurements. Two solar wind shocks occurred within 25 hr, generating four distinct periods of GIC. Two of the GIC events were associated with the arrival of the shocks themselves. These generated large but short-lived GIC effects that resulted in no observable harmonic generation. Nearby and more distant magnetometers showed good agreement in measuring these global-scale magnetic field perturbations. However, two subsequent longer-lasting GIC periods, up to 30 min in duration, generated harmonics detected by the VLF receiver systems, when GIC levels continuously exceeded 15 A in T4. Nearby and more distant magnetometers showed differences in their measurements of the magnetic field perturbations at these times, suggesting the influence of small-scale ionospheric current structures close to Dunedin. VLF receiver systems picked up harmonics from the substation, up to the 30th harmonic, consistent with observed high-voltage increases in even harmonic distortion, along with small decreases in odd harmonic distortion.

Extreme solar events **Review**

Edward W. **Cliver**, Carolus J. Schrijver, Kazunari Shibata & Ilya G. Usoskin

Living Reviews in Solar Physics volume 19, Article number: 2 (**2022**)
https://link.springer.com/content/pdf/10.1007/s41116-022-00033-8.pdf

We trace the evolution of research on extreme solar and solar-terrestrial events from the 1859 Carrington event to the rapid development of the last twenty years. Our focus is on the largest observed/inferred/theoretical cases of sunspot groups, flares on the Sun and Sun-like stars, coronal mass ejections, solar proton events, and geomagnetic storms. The reviewed studies are based on modern observations, historical or long-term data including the auroral and cosmogenic radionuclide record, and Kepler observations of Sun-like stars. We compile a table of 100- and 1000-year events based on occurrence frequency distributions for the space weather phenomena listed above. Questions considered include the Sun-like nature of superflare stars and the existence of impactful but unpredictable solar "black swans" and extreme "dragon king" solar phenomena that can involve different physics from that operating in events which are merely large. **774 AD, 17 Sep 1770, 1 September 1859, 4 Feb 1872, 14-15 May 1921, 28 Feb 1942, 5 April 1947, 23 May 1967, 2–11 August 1972 , 29 Apr 1973, 21 Apr 2002, 28 October 2003; 6, 13, 14 Dec 2006, 9 Nov 2011, 28 Oct 2013, 4 Nov 2015**

Table 5 Historical fast transit ICME events

The 1859 space weather event revisited: limits of extreme activity

Edward W. **Cliver**1* and William F. Dietrich2

J. Space Weather Space Clim., Volume 3, **2013**, A31; **File**

The solar flare on 1 September 1859 and its associated geomagnetic storm remain the standard for an extreme solar-terrestrial event. The most recent estimates of the flare soft X-ray (SXR) peak intensity and Dst magnetic storm index for this event are: SXR class = X45 (±5) (vs. X35 (±5) for the 4 November 2003 flare) and minimum Dst = −900 (+50, −150) nT (vs. −825 to −900 nT for the great storm of May 1921). We have no direct evidence of an associated solar energetic proton (SEP) event but a correlation between >30 MeV SEP fluence (F30) and flare size based on modern data yields a best guess F30 value of ~1.1 × 1010 pr cm−2 (with the ±1σ uncertainty spanning a range from ~109–1011 pr cm−2) for a composite (multi-flare plus shock) 1859 event. This value is approximately twice that of estimates/measurements – ranging from ~5–7 × 109 pr cm−2 – for the largest SEP episodes (July 1959, November 1960, August 1972) in the modern era.

PRESTO – Predictability of the Variable Solar-Terrestrial Coupling
Pillar 3: Solar activity and its influence on climate

L. C. A. O. **Coddington**1, J. Jiang2 and E. Rozanov3

SCOSTEP__PRESTO Newsletter **2020** **File**

Automated Solar Activity Prediction: A hybrid computer platform using machine learning and solar imaging for automated prediction of solar flares

T. **Colak** & R. Qahwaji
Space Weather, Vol. 7, No. 6, S06001, **2009**
http://dx.doi.org/10.1029/2008SW000401

The importance of real-time processing of solar data especially for space weather applications is increasing continuously. In this paper, we present an automated hybrid computer platform for the short-term prediction of significant solar flares using SOHO/Michelson Doppler Imager images. This platform is called the Automated Solar Activity Prediction tool (ASAP). This system integrates image processing and machine learning to deliver these predictions. A machine learning-based system is designed to analyze years of sunspot and flare data to create associations that can be represented using computer-based learning rules. An imaging-based real-time system that provides automated detection, grouping, and then classification of recent sunspots based on the McIntosh classification is also created and integrated within this system. The properties of the sunspot regions are extracted automatically by the imaging system and processed using the machine learning rules to generate the real-time predictions. Several performance measurement criteria are used and the results are provided in this paper. Also, quadratic score is used to compare the prediction results of ASAP with NOAA Space Weather Prediction Center (SWPC) between 1999 and 2002, and it is shown that ASAP generates more accurate predictions compared to SWPC.

Space Weather: Its Effects and Predictability,

D. G. **Cole**
Space Sci. Rev. **107** (1–2), 295–302 (**2003**).

Terrestrial technology is now, and increasingly, sensitive to space weather. Most space weather is caused by solar storms and the resulting changes to the Earth's radiation environment and the magnetosphere. The Sun as the driver of space weather is under intense observation but remains to be adequately modelled. Recent spacecraft measurements are greatly improving models of solar activity, the interaction of the solar wind with the magnetosphere, and models of the radiation belts. In-situ data updates the basic magnetospheric model to provide specific details of high-energy electron flux at satellite orbits. Shock wave effects at the magnetopause can also be coarsely predicted. However, the specific geomagnetic effects at ground level depend on the calculation of magnetic and electric fields and further improvements are needed. New work on physical models is showing promise of raising geomagnetic and ionospheric predictability above the synoptic climatological level.

Flight safety implications of the extreme solar proton event of 23 February 1956

Kyle **Copeland**, William Atwell
Adv. Space Res. 63 (**2019**) 665-671
https://www.sciencedirect.com/science/article/pii/S0273117718308433

There is considerable speculation about the effects at aircraft altitudes resulting from extreme solar proton events. The ground level event (GLE) of 23 February 1956 (GLE 5), remains the largest solar proton event of the neutron monitor era in terms of its influence on count rates at monitors near sea level. During this GLE the count rate was increased by as much as 4760% (15-min average) at the Leeds monitor relative to the count rate from galactic cosmic radiation (GCR). Two modern models of the event cumulative solar proton spectrum for this event, a 6-parameter fit in energy and a 4-parameter Band fit in rigidity, are compared with 1-h of GCR at solar minimum. While effective doses calculated with CARI-7A for both models at low geomagnetic cutoff rigidities are indeed high when compared with GCR and can exceed recommended exposure limits, both GLE spectra exhibit a much stronger dependence on cutoff rigidity than GCR, and a larger fraction of the dose from neutrons. At locations with cutoff rigidities above 4.2 and 6.4 GV, respectively, the GLE effective doses are smaller than the GCR hourly dose. At locations with cutoff rigidities above about 4 GV, GCR was the dominant source of exposure in 10 h or less at all altitudes examined. This suggests that if a similar event occurs in the future, low- and mid-latitude flights at modern jet flight altitudes could be well-protected by Earth's magnetic field.

Solar Cosmic Ray Dose Rate Assessments During GLE 72 Using MIRA and PANDOCA

Kyle **Copeland**, Daniel Matthiä, Matthias M. Meier
Space Weather Volume16, Issue8 August **2018** Pages 969-976 **2018**
http://sci-hub.tw/10.1029/2018SW001917

Ground level enhancement (GLE) 72, which occurred **10 September 2017**, is the most recent of two solar particle-induced enhancements in ground level measurements of cosmic radiation secondary neutrons in solar cycle 24. GLEs have been unusually rare in this solar cycle. GLEs can significantly increase ionizing radiation dose rates at aviation altitudes for hours to days, leading to concern among crewmembers. Real-time monitoring and preliminary evaluation of solar proton events, including GLEs, in regard to effective dose rates at aviation altitudes has been ongoing since the U.S. Federal Aviation Administration began operating its Solar Radiation Alert System (SRAS) in 2002. Since then, SRAS has been revised multiple times. In this report, model calculations of dose rates during GLE 72 from Maps of Ionizing Radiation in the Atmosphere (MIRA), the latest SRAS software based on CARI-7A, are compared with those from the model Professional Aviation Dose Calculator (PANDOCA) developed by the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt). At very low cutoff rigidities model calculations agree within 40% and indicate no significant increase in radiation exposures at commercial aviation altitudes. The larger than expected differences at very low cutoff rigidities indicate Geostationary Orbiting Environmental Satellite particle flux data alone that are insufficient to produce consistent solar particle dose estimates.

Geomagnetic Storm Risks to Air-Breathing Electric Propulsion Missions

Crandall, P (Crandall, Patrick) ; Piccone, V (Piccone, Vasily) ; Asanuma, T (Asanuma, Taiga) ; Wirz, RE (Wirz, Richard E.)

IEEE Aerospace Conference Proceedings **2024**

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Geomagnetic storms can cause significant and rapid increases in atmospheric density at very low Earth orbit (VLEO) altitudes potentially putting a VLEO spacecraft into an unrecoverable orbit. Air-breathing electric propulsion (ABEP) spacecraft may be more susceptible to geomagnetic storms due to the low thrust-to-drag chosen for many proposed spacecraft. For ABEP missions to become viable, risks due to geomagnetic storms must be mitigated. This work explores geomagnetic storm risks to ABEP spacecraft using an orbit propagator. Spacecraft with low ballistic coefficient and low thrust-to-drag are identified as highly susceptible to geomagnetic storm risks. Two risk mitigation strategies are investigated for these spacecraft: (1) preemptive orbit raising ahead of a storm, and (2) using onboard xenon propellant to increase thruster performance during a storm. An orbit propagator is used to investigate performance of these risk mitigation strategies during a G4 (severe) geomagnetic storm in November 2004. It is shown that preemptive orbit raising successfully mitigates geomagnetic storm risks for spacecraft with higher thrust-to-drag while adding a relatively small amount of xenon propellant mitigates geomagnetic storm risk for all spacecraft.

Predicting Space Weather, Protecting Satellites

Leah **Crane**

Eos Buzz Newsletter: 5 August **2016** **EOS,** *97*,doi:10.1029/2016EO056621.

https://eos.org/research-spotlights/predicting-space-weather-protecting-satellites

A new model predicts electron and ion fluxes at geosynchronous orbit an hour ahead of time, allowing satellite operators to protect their instruments.

Origins of the Ambient Solar Wind: Implications for Space Weather **Review**

Steven R. **Cranmer** (CU Boulder), Sarah E. Gibson (HAO), Pete Riley (PSI)

Space Science Reviews. Volume 212, Issue 3–4, pp 1345–1384 **2017**

Special issue connected with a 2016 ISSI workshop on "The Scientific Foundations of Space Weather."

https://arxiv.org/pdf/1708.07169.pdf

https://link.springer.com/content/pdf/10.1007%2Fs11214-017-0416-y.pdf

The Sun's outer atmosphere is heated to temperatures of millions of degrees, and solar plasma flows out into interplanetary space at supersonic speeds. This paper reviews our current understanding of these interrelated problems: coronal heating and the acceleration of the ambient solar wind. We also discuss where the community stands in its ability to forecast how variations in the solar wind (i.e., fast and slow wind streams) impact the Earth. Although the last few decades have seen significant progress in observations and modeling, we still do not have a complete understanding of the relevant physical processes, nor do we have a quantitatively precise census of which coronal structures contribute to specific types of solar wind. Fast streams are known to be connected to the central regions of large coronal holes. Slow streams, however, appear to come from a wide range of sources, including streamers, pseudostreamers, coronal loops, active regions, and coronal hole boundaries. Complicating our understanding even more is the fact that processes such as turbulence, stream-stream interactions, and Coulomb collisions can make it difficult to unambiguously map a parcel measured at 1 AU back down to its coronal source. We also review recent progress -- in theoretical modeling, observational data analysis, and forecasting techniques that sit at the interface between data and theory -- that gives us hope that the above problems are indeed solvable.

Editorial: Towards Future Research on Space Weather Drivers

Hebe **Cremades**, Teresa Nieves-Chinchilla & Cristina H. Mandrini

Solar Physics volume 296, Article number: 168 (**2021**)

https://link.springer.com/content/pdf/10.1007/s11207-021-01919-w.pdf
https://doi.org/10.1007/s11207-021-01919-w
The workshop "Towards Future Research on Space Weather Drivers" brought together 120 heliophysicists from the international community. The workshop was held in the city of San Juan, Argentina, from 2 to 9 July 2019, with the kick-off of the meeting being marked by the total solar eclipse on 2 July.

A tool to improve space weather forecasts: Kilometric radio emissions from Wind/WAVES

To improve predictions of the arrival time of magnetohydrodynamic shock, which can occur as coronal mass ejections propagate through interplanetary space, scientists study low frequency radio emissions detected by the WIND/WAVES satellite.

Cremades, H.; St. Cyr, O. C.; Kaiser, M. L.

Space Weather, Vol. 5, No. 8, S08001, **2007, File**

http://dx.doi.org/10.1029/2007SW000314

For decades, space environment forecasters have used the appearance of metric Type II radio emission as a proxy for eruptions in the solar corona. The drift rate of these near-Sun emissions is often turned into a speed, commonly assumed to be that of an MHD shock. However, their utility to forecast shock arrival times has not proved to be conclusive. Metric emissions can be detected by ground-based antennae, while lower-frequency components of these slowly drifting emissions can also be tracked by spacecraft in interplanetary space, as far down in frequency as that of the local plasma frequency. For a spacecraft at L1, this corresponds to about 25 kHz, or an electron density of about 7 cm−3 in the ambient solar wind. Here we report a recent study that aims to improve the predictions of shock arrival time at L1 by means of the low-frequency emissions detected by WIND/WAVES. This technique, implemented on an extensive sample of hectometric and kilometric type II radio bursts, has yielded promising results.

Table

Five Centuries of Exploration: From Distant Shores to Distant Planets

Crosby, Norma B.; Van den Bergh, Iwan; Bollen, Robrecht; Brabants, Jan; Cops, Jirka; Dillen, Yцrg; Doomen, Cйline; Lambrechts, Jonas; Stulens, Thomas; Адron, Trippaers; Vanlaer, Lucas; Vinkesteijn, Sebastiaan

Space Weather, Vol. 10, No. 3, S03007, **2012**

http://dx.doi.org/10.1029/2011SW000658

Examining an era of intense technological development aimed at expanding the boundaries of the known world. Throughout time humans have been born with the curiosity to explore. Crossing the oceans on Earth to those in interplanetary space, the motivations behind exploration by humanity have not changed profoundly during these last five centuries. Some of the obstacles that were met by the explorers in the past and those that we will encounter in the future are similar, funding issues being one such topic. However, obstacles regarding the environmental conditions that will be encountered in interplanetary space are very different from those found on Earth. Indeed, the space weather that presides in interplanetary space is unlike anything we are familiar with in our daily lives. However, be it an ocean storm or a solar storm, the objective remains the same - to understand and protect the transportation device and the crew against the environment that it will encounter.

Space weather: science and effects

Norma B. **Crosby**

Universal Heliophysical Processes Proceedings IAU Symposium No. 257, 2008, N. Gopalswamy & D.F. Webb, eds, pp.47-56, **2009, File**.

From the point-of-view of somebody standing outside on a cold winter night looking up at a clear cloudless sky, the space environment seems to be of a peaceful and stable nature. Instead, the opposite is found to be true. In fact the space environment is very dynamic on all spatial and temporal scales, and in some circumstances may have unexpected and hazardous effects on technology and humans both in space and on Earth. In fact the space environment seems to have a weather all of its own – its own "space weather". Our Sun is definitely the driver of our local space weather. Space weather is an interdisciplinary subject covering a vast number of technological, scientific, economic and environmental issues. It is an applicationoriented discipline which addresses the needs of "space weather product" users. It can be truly said that space weather affects everybody, either directly or indirectly. The aim of this paper is to give an overview of what space weather encompasses, emphasizing how solar-terrestrial physics is applied to space weather. Examples of "space weather product" users will be given highlighting those products that we as a civilization are most dependent on.

Solar extreme events 2005–2006: Effects on near-Earth space systems and interplanetary systems
N.B. **Crosby**
Advances in Space Research
Volume 43, Issue 4, 16 February **2009**, Pages 559-564
Extreme events are defined as those events in which the characteristics (e.g. field strength, speed, intensity of radiation, energies) of the associated phenomena (e.g. solar flares, coronal mass ejections, solar proton events) are some orders of magnitude larger than in other events. Such strong events commonly occur about two years before and after sunspot maximum and some strong events occur as well in the declining phase before the solar activity minimum [Bothmer V., Zhukov A. The 11 Sun as the prime source of space weather, in: Bothmer, V., Daglis, I. (Eds.), Space Weather: Physics and Effects, Springer Praxis Books, 12 pp. 438, 2007]. In the first part of the paper the characteristics of the Jan. 2005 and Dec. 2006 events are given. This is followed by a presentation of the effects that were encountered on technological systems and also addresses the issue of what could have occurred on biological systems during such events. The second part of the paper deals with how one should go about analyzing solar extreme events - as part of the global distribution of all events or as "outliers" with their own special characteristics.

Interplanetary Space Weather and Its Planetary Connection

Crosby, N., V. Bothmer, R. Facius, J.-M. Grießmeier, X. Moussas, M. Panasyuk, N. Romanova, and P. Withers ,
Space Weather, *6*, S01003, doi:10.1029/2007SW000361, (**2008**).
Interplanetary travel is not just a science fiction scenario anymore, but a goal as realistic as when our ancestors started to cross the oceans. With curiosity driving humans to visit other planets in our solar system, the understanding of interplanetary space weather is a vital subject today, particularly because the physical conditions faced during a space vehicle's transit to its targeted solar system object are crucial to a mission's success and vital to the health and safety of spacecraft crew, especially when scheduling planned extravehicular activities.

Chapter 23 - Extreme Ionospheric Storms and Their Effects on GPS Systems
Review
Geoff **Crowley**, IrfanAzeem
In: Extreme Events in Geospace Origins, Predictability, and Consequences **2018**, Pages 555-586
http://sci-hub.tw/10.1016/B978-0-12-812700-1.00023-6
Given the central importance of Global Positioning System (GPS) to modern society, it is important to consider the effects of extreme ionospheric storms on GPS signals. We describe the ionosphere and ionospheric storms, and the main ionospheric effects on GPS caused by gradients in TEC, by scintillation and by Traveling Ionospheric Disturbances. We summarize the GPS impacts of the three largest ionospheric storms of the last 15 years. Finally, we discuss the implications for extreme ionospheric storms and their effects on operational systems, with a focus on GPS-reliant systems. We note that GPS outages can affect not only the surveyor (positioning) or farmer (precision agriculture), but also the critical infrastructure, including financial institutions, transportation, communications, and the internet, and perhaps most importantly, the power grid, which relies on timing signals provided by the GPS system. While mitigation efforts are important, it is also vital to continue fundamental research to better understand ionospheric variability.

Validation of the NOAA Space Weather Prediction Center's solar flare forecasting look-up table and forecaster-issued probabilities,
Misty D. **Crown**
Space Weather, 10, S06006, doi:10.1029/2011SW000760. **2012**
This paper provides an assessment of the operational solar flare look-up table currently in use at the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC) during solar cycle 23 (May 1996 – December 2008). To assess the value of human interaction, a validation of subjective flare probability forecasts was conducted and compared to the results obtained from the climatological look-up table used at SWPC. Probabilistic flare forecasts are evaluated using the Brier Skill Score, then discretized and entered into contingency tables from which a variety of verification measures are calculated. The ultimate goal of this report is to provide an operational baseline, whereby the scores and statistics from this paper can be used as the basis for future evaluation of models presented to the operational community.

Space radiation risk limits and Earth-Moon-Mars environmental models
Cucinotta, Francis A.; Hu, Shaowen; Schwadron, Nathan A.; Kozarev, K.; Townsend, Lawrence W.; Kim, Myung-Hee Y.

Space Weather, Vol. 8, No. 12?, S00E09, 12 PP., **2010**
http://dx.doi.org/10.1029/2010SW000572
We review NASA's short-term and career radiation limits for astronauts and methods for their application to future exploration missions outside of low Earth orbit. Career limits are intended to restrict late occurring health effects and include a 3% risk of exposure-induced death from cancer and new limits for central nervous system and heart disease risks. Short-term dose limits are used to prevent in-flight radiation sickness or death through restriction of the doses to the blood forming organs and to prevent clinically significant cataracts or skin damage through lens and skin dose limits, respectively. Large uncertainties exist in estimating the health risks of space radiation, chiefly the understanding of the radiobiology of heavy ions and dose rate and dose protraction effects, and the limitations in human epidemiology data. To protect against these uncertainties NASA estimates the 95% confidence in the cancer risk projection intervals as part of astronaut flight readiness assessments and mission design. Accurate organ dose and particle spectra models are needed to ensure astronauts stay below radiation limits and to support the goal of narrowing the uncertainties in risk projections. Methodologies for evaluation of space environments, radiation quality, and organ doses to evaluate limits are discussed, and current projections for lunar and Mars missions are described.

Geomagnetic solar flare effects: a review

Juan José **Curto***
J. Space Weather Space Clim. **2020**, **10**, 27
https://www.swsc-journal.org/articles/swsc/pdf/2020/01/swsc190079.pdf
https://doi.org/10.1051/swsc/2020027
Solar flare effects (Sfe) are rapid variations in the Earth's magnetic field and are related to the enhancement of the amount of radiation produced during Solar flare events. They mainly appear in the Earth's sunlit hemisphere at the same time as the flare observation and have a crochet-like shape. Much progress has been made since Carrington's first observations in 1859 which are considered to represent the first direct evidence of the connection between the Sun and the Earth's environment but there is still much to discover. In this paper, we review state-of-the-art developments and the advances made in the knowledge concerning Sfe phenomena while also looking at the challenges that lie ahead. First, we offer a historical approach with a comprehensive description that allows for a better understanding of the main characteristics of Sfe. This frames specific topics like the puzzling reversed-Sfe or the nighttime Sfe. The role played by the Service of Rapid Magnetic variations (SRMV) is also assessed, followed by a discussion of the main current limiting factors in the process of detection and proposed ways to overcome challenges such as by creating an automatic detection method. The paper clarifies some aspects related to the geo-effectiveness of the solar flares producing magnetic disturbances. The importance of the global modelling studies covering critical aspects needed to understand this Sun–Earth system is assessed. Also, we provide an overview of the temporal evolution of the electric currents producing Sfe. The importance of key subjects such as the dynamic aspects of Sfe is developed in another section. Finally, estimations of the size of large flares using ionospheric and magnetic data are reviewed as well as the prospects of these large flare events putting technological systems in danger.

Confirming geomagnetic Sfe by means of a solar flare detector based on GNSS

Juan José **Curto**1,*, José Miguel Juan2 , and Cristhian Camilo Timoté2
J. Space Weather Space Clim. **2019**, 9, A42
https://www.swsc-journal.org/articles/swsc/pdf/2019/01/swsc190038.pdf
Solar Flares (SF) refer to sudden increases of electromagnetic radiation from the Sun lasting from minutes to hours. Irradiance in the Extremely Ultra-Violet (EUV) or X band is enhanced and it can produce a sudden over-ionization in the ionosphere, which can be tracked by several techniques. On the one hand, this over-ionization increases the ionospheric delays of GNSS signals in such a way as can be monitored using measurements collected by dual-frequency GNSS receivers. On the other hand, this over-ionization of the ionosphere is the origin of electrical currents which, in turn, induce magnetic fields which can be monitored with ground magnetometers. In this work we propose the use of a GNSS Solar Flare Monitor (GNSS-SF) for its utility to confirm the presence of ionospheric ionization which is able to produce Solar Flare Effects (Sfe) in geomagnetism. A period of 11 years (2008–2018) has been analyzed and contingency tables are shown. Although most of the GNSS-SF detections coincide with SF and most of the Sfe have a detected origin in the ionosphere, there are some paradoxes: sometimes small flares produce disturbances which are clearly detected by both methods while other disturbances, originated by powerful flares, go by virtually unnoticed. We analyzed some of these cases and proposed some explanations. We found that suddenness in the variation is a key factor for detection. Threshold values of the velocity of change to remove the background noise and the use of the acceleration of change instead of the velocity of change as the key performance detector are other topics we deal with in this paper. We conclude that the GNSS-SF detector could provide warnings of ionization disturbances from SF covering the time when the Sfe detectors are "blind", and can help to confirm Sfe events when Sfe detectors are not able to give a categorical answer**. August 8 2011, May 13, 2013, July 8, 2013, June 10 2014, 10-11 March 2015, August 18, 2017, September 6, 2017, September 10, 2017**
Comments: J. Space Weather Space Clim. Volume 10, paper 15, **2020**

https://www.swsc-journal.org/articles/swsc/pdf/2020/01/swsc190087.pdf
Answer to the comments: J. Space Weather Space Clim. Volume 10, paper 16, **2020**
https://www.swsc-journal.org/articles/swsc/pdf/2020/01/swsc200005.pdf

Solar energetic particle warnings from a coronagraph

O. C. St. **Cyr**, A. Posner, J. T. Burkepile
Space Weather Volume 15, Issue 1 January **2017** Pages 240–257
http://sci-hub.cc/10.1002/2016SW001545
We report here the concept of using near-real time observations from a coronagraph to provide early warning of a fast coronal mass ejection (CME) and the possible onset of a solar energetic particle (SEP) event. The **1 January 2016**, fast CME, and its associated SEP event are cited as an example. The CME was detected by the ground-based K-Cor coronagraph at Mauna Loa Solar Observatory and by the SOHO Large Angle and Spectrometric Coronagraph. The near-real-time availability of the high-cadence K-Cor observations in the low corona leads to an obvious question: "Why has no one attempted to use a coronagraph as an early warning device for SEP events?" The answer is that the low image cadence and the long latency of existing spaceborne coronagraphs make them valid for archival studies but typically unsuitable for near-real-time forecasting. The January 2016 event provided favorable CME viewing geometry and demonstrated that the primary component of a prototype ground-based system for SEP warnings is available several hours on most days. We discuss how a conceptual CME-based warning system relates to other techniques, including an estimate of the relative SEP warning times, and how such a system might be realized.

2. Existing SEP Forecasting Techniques

Predictability of variable solar–terrestrial coupling **Review**

Ioannis A. **Daglis**1,15, Loren C. Chang2, Sergio Dasso3, Nat Gopalswamy4, Olga V. Khabarova5, Emilia Kilpua6, Ramon Lopez7, Daniel Marsh8,16, Katja Matthes9,17, Dibyendu Nandy10,18, Annika Seppälä11, Kazuo Shiokawa12, Rémi Thiéblemont13, and Qiugang Zong
Ann. Geophys., 39, 1013–1035, **2021** **File**
https://doi.org/10.5194/angeo-39-1013-2021
https://angeo.copernicus.org/articles/39/1013/2021/angeo-39-1013-2021.pdf
In October 2017, the Scientific Committee on Solar-Terrestrial Physics (SCOSTEP) Bureau established a committee for the design of SCOSTEP's Next Scientific Programme (NSP). The NSP committee members and authors of this paper decided from the very beginning of their deliberations that the predictability of the Sun–Earth System from a few hours to centuries is a timely scientific topic, combining the interests of different topical communities in a relevant way. Accordingly, the NSP was christened PRESTO – PREdictability of the variable Solar–Terrestrial cOupling. This paper presents a detailed account of PRESTO; we show the key milestones of the PRESTO roadmap for the next 5 years, review the current state of the art and discuss future studies required for the most effective development of solar–terrestrial physics.
PRESTO – https://www.issibern.ch/wp-content/uploads/2020/03/SCOSTEP_Taikong13.pdf

From solar sneezing to killer electrons: outer radiation belt response to solar eruptions **Review**

Ioannis A. **Daglis**, Christos Katsavrias and Marina Georgiou
Philosophical Transactions of the Royal Society A v. 377 Issue 2148 Article ID:_20180097 **2019**
https://royalsocietypublishing.org/doi/pdf/10.1098/rsta.2018.0097
Electrons in the outer Van Allen (radiation) belt occasionally reach relativistic energies, turning them into a potential hazard for spacecraft operating in geospace. Such electrons have secured the reputation of satellite killers and play a prominent role in space weather. The flux of these electrons can vary over time scales of years (related to the solar cycle) to minutes (related to sudden storm commencements). Electric fields and plasma waves are the main factors regulating the electron transport, acceleration and loss. Both the fields and the plasma waves are driven directly or indirectly by disturbances originating in the Sun, propagating through interplanetary space and impacting the Earth. This paper reviews our current understanding of the response of outer Van Allen belt electrons to solar eruptions and their interplanetary extensions, i.e. interplanetary coronal mass ejections and high-speed solar wind streams and the associated stream interaction regions.

AME: A Cross-Scale Constellation of CubeSats to Explore Magnetic Reconnection in the Solar–Terrestrial Relation with **Review**

Lei Dai1*, Chi Wang1, Zhiming Cai2, Walter Gonzalez1,3, … Lev Zelenyi18, Elena E. Grigorenko18, et al.
Front. Phys., 15 April **2020** | https://doi.org/10.3389/fphy.2020.00089

https://www.frontiersin.org/articles/10.3389/fphy.2020.00089/full
https://sci-hub.tw/10.3389/fphy.2020.00089
THIS ARTICLE IS PART OF THE RESEARCH TOPIC
Space Weather with Small Satellites View all Articles
A major subset of solar–terrestrial relations, responsible, in particular, for the driver of space weather phenomena, is the interaction between the Earth's magnetosphere and the solar wind. As one of the most important modes of the solar–wind–magnetosphere interaction, magnetic reconnection regulates the energy transport and energy release in the solar–terrestrial relation. In situ measurements in the near-Earth space are crucial for understanding magnetic reconnection. Past and existing spacecraft constellation missions mainly focus on the measurement of reconnection on plasma kinetic-scales. Resolving the macro-scale and cross-scale aspects of magnetic reconnection is necessary for accurate assessment and predictions of its role in the context of space weather. Here, we propose the **AME (self-Adaptive Magnetic reconnection Explorer)** mission consisting of a cross-scale constellation of 12+ CubeSats and one mother satellite. Each CubeSat is equipped with instruments to measure magnetic fields and thermal plasma particles. With multiple CubeSats, the AME constellation is intended to make simultaneous measurements at multiple scales, capable of exploring cross-scale plasma processes ranging from kinetic scale to macro scale.

Unveiling the space weather during the Starlink satellites destruction event on 4 February 2022
Tong **Dang**, Xiaolei Li, Bingxian Luo, Ruoxi Li, Binzheng Zhang, Kevin Pham, Dexin Ren, Xuetao Chen, Jiuhou Lei, Yuming Wang
Space Weather e2022SW003152 **Volume20, Issue8** **2022**
https://doi.org/10.1029/2022SW003152
https://gupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022SW003152
On 4 February 2022, 38 Starlink satellites were destroyed by the geomagnetic storm, which brought significant financial, aerospace and public influences. In this letter, we reveal the space weather process during 3-4 February 2022 geomagnetic disturbances, from the Sun all the way to the satellite orbiting atmosphere. Initiated by an M1.0 class flare and the following coronal mass ejection (CME), a moderate geomagnetic storm was stimulated on February 3rd by the CME arrival at Earth. Subsequently, another moderate storm was triggered on February 4th by the passage of another CME. Model simulations driven by solar wind show that the first geomagnetic storm induced around 20% atmospheric density perturbations at 210 km altitude on February 3rd. The unexpected subsequent storm on February 4th led to a density enhancement of around 20%-30% at around 210 km. The resulting atmospheric drag can be even larger, since the regional density enhancement was over 60% and the satellite orbits were continuously decaying. This event brings forth the urgent requirements of better understanding and accurate prediction of the space weather as well as collaborations between industry and space weather community.
See https://www.spaceweather.com on 16 Sep 2022

Space weather at the Institution of Engineering and Technology
Chris **Davis**
UKSP nugget: 28, Oct **2012**
About the Meeting “Solar Storms: Predicting and protecting against geomagnetic storms”.
Доступук к файлам докладов
http://tv.theiet.org/search.cfm?search=1&back=%2Findex.cfm&syear=2012&schan=46&stext=

A comparison of space weather analysis techniques used to predict the arrival of the Earth-directed CME and its shockwave launched on 8 April 2010
Davis, C. J.; de Koning, C. A.; Davies, J. A.; Biesecker, D.; Millward, G.; Dryer, M.; Deehr, C.; Webb, D. F.; Schenk, K.; Freeland, S. L.; MЖstl, C.; Farrugia, C. J.; Odstrcil, D.
Space Weather, Vol. 9, No. 1, S01005, **2011, File**
The Earth-directed coronal mass ejection (CME) of **8 April 2010** provided an opportunity for space weather predictions from both established and developmental techniques to be made from near–real time data received from the SOHO and STEREO spacecraft; the STEREO spacecraft provide a unique view of Earth-directed events from outside the Sun-Earth line. Although the near–real time data transmitted by the STEREO Space Weather Beacon are significantly poorer in quality than the subsequently downlinked science data, the use of these data has the advantage that near–real time analysis is possible, allowing actual forecasts to be made. The fact that such forecasts cannot be biased by any prior knowledge of the actual arrival time at Earth provides an opportunity for an unbiased comparison between several established and developmental forecasting techniques. We conclude that for forecasts

based on the STEREO coronagraph data, it is important to take account of the subsequent acceleration/deceleration of each CME through interaction with the solar wind, while predictions based on measurements of CMEs made by the STEREO Heliospheric Imagers would benefit from higher temporal and spatial resolution. Space weather forecasting tools must work with near–real time data; such data, when provided by science missions, is usually highly compressed and/or reduced in temporal/spatial resolution and may also have significant gaps in coverage, making such forecasts more challenging.

The utility of polarized heliospheric imaging for space weather monitoring

C. E. **DeForest**, T. A. Howard, D. F. Webb, J. A. Davies

Space Weather Volume 14, Issue 1 January **2016** Pages 32–49

http://onlinelibrary.wiley.com/doi/10.1002/2015SW001286/full

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2015SW001286

A polarizing heliospheric imager is a critical next generation tool for space weather monitoring and prediction. Heliospheric imagers can track coronal mass ejections (CMEs) as they cross the solar system, using sunlight scattered by electrons in the CME. This tracking has been demonstrated to improve the forecasting of impact probability and arrival time for Earth-directed CMEs. Polarized imaging allows locating CMEs in three dimensions from a single vantage point. Recent advances in heliospheric imaging have demonstrated that a polarized imager is feasible with current component technology.Developing this technology to a high technology readiness level is critical for space weather relevant imaging from either a near-Earth or deep-space mission. In this primarily technical review, we developpreliminary hardware requirements for a space weather polarizing heliospheric imager system and outline possible ways to flight qualify and ultimately deploy the technology operationally on upcoming specific missions. We consider deployment as an instrument on NOAA's Deep Space Climate Observatory follow-on near the Sun-Earth L1 Lagrange point, as a stand-alone constellation of smallsats in low Earth orbit, or as an instrument located at the Sun-Earth L5 Lagrange point. The critical first step is the demonstration of the technology, in either a science or prototype operational mission context.

First Joint Observations of the Space Weather Events over Mexico

V. **De la Luz**, J.A González-Esparza, M.A. Sergeeva, P. Corona-Romero, L.X. González, J. Mejía-Ambriz,J.F. Valdés-Galicia, E. Aguilar-Rodríguez, M. Rodríguez-Martínez, E. Romero-Hernández, E. Andrade, P. Villanueva, E. Huipe-Domratcheva, G. Cifuentes, E. Hernandez, C. Monstein

Annales Geophysicae (ANGEO) **2018**

https://arxiv.org/pdf/1808.07425.pdf

The Mexican Space Weather Service (SCiESMEX in Spanish) and National Space Weather Laboratory (LANCE in Spanish) were organized in 2014 and in 2016 respectively to provide space weather monitoring and alerts, as well as scientific research in Mexico. In this work, we present the results of the first joint observations of two events (**22 June, 2015, and 29 September, 2015**) with our local network of instruments and their related products. This network includes the MEXART radio telescope (solar flare and radio burst), the Compact Astronomical Low-frequency, Low-cost Instrument for Spectroscopy in Transportable Observatories (CALLISTO) at MEXART station (solar radio burst), the Mexico City Cosmic Ray Observatory (cosmics ray fluxes), GPS receiver networks (ionospheric disturbances), and the Geomagnetic Observatory of Teoloyucan (geomagnetic field). The observations show that we detected significant space weather effects over the Mexican territory: geomagnetic and ionospheric disturbances (22 June, 2015), variations in cosmic rays fluxes, and also radio communications interferences (29 September, 2015). The effects of these perturbations were registered, for the first time, using space weather products by SCiESMEX: TEC maps, regional geomagnetic index K mex , radio spectrographs of low frequency, and cosmic rays fluxes. These results prove the importance of monitoring space weather phenomena in the region and the need to strengthening the instrumentation network.

Supervised classification of solar features using prior information

Ruben **De Visscher**1*, Véronique Delouille1, Pierre Dupont2 and Charles-Alban Deledalle

J. Space Weather Space Clim., 5, A34 (**2015**)

http://www.swsc-journal.org/articles/swsc/pdf/2015/01/swsc140058.pdf

Context: The Sun as seen by Extreme Ultraviolet (EUV) telescopes exhibits a variety of large-scale structures. Of particular interest for space-weather applications is the extraction of active regions (AR) and coronal holes (CH). The next generation of GOES-R satellites will provide continuous monitoring of the solar corona in six EUV bandpasses that are similar to the ones provided by the SDO-AIA EUV telescope since May 2010. Supervised segmentations of EUV images that are consistent with manual segmentations by for example space-weather forecasters help in extracting useful information from the raw data.
Aims: We present a supervised segmentation method that is based on the Maximum A Posteriori rule. Our method allows integrating both manually segmented images as well as other type of information. It is applied on SDO-AIA images to segment them into AR, CH, and the remaining Quiet Sun (QS) part.

Methods: A Bayesian classifier is applied on training masks provided by the user. The noise structure in EUV images is non-trivial, and this suggests the use of a non-parametric kernel density estimator to fit the intensity distribution within each class. Under the Naive Bayes assumption we can add information such as latitude distribution and total coverage of each class in a consistent manner. Those information can be prescribed by an expert or estimated with an Expectation-Maximization algorithm.
Results: The segmentation masks are in line with the training masks given as input and show consistency over time. Introduction of additional information besides pixel intensity improves upon the quality of the final segmentation.
Conclusions: Such a tool can aid in building automated segmentations that are consistent with some ground truth' defined by the users.

The utility of polarized heliospheric imaging for space weather monitoring

C. E. **DeForest**, T. A. Howard, D. F. Webb, J. A. Davies

Space Weather Volume 14, Issue 1 January **2016** Pages 32–49

A polarizing heliospheric imager is a critical next generation tool for space weather monitoring and prediction. Heliospheric imagers can track coronal mass ejections (CMEs) as they cross the solar system, using sunlight scattered by electrons in the CME. This tracking has been demonstrated to improve the forecasting of impact probability and arrival time for Earth-directed CMEs. Polarized imaging allows locating CMEs in three dimensions from a single vantage point. Recent advances in heliospheric imaging have demonstrated that a polarized imager is feasible with current component technology.Developing this technology to a high technology readiness level is critical for space weather relevant imaging from either a near-Earth or deep-space mission. In this primarily technical review, we developpreliminary hardware requirements for a space weather polarizing heliospheric imager system and outline possible ways to flight qualify and ultimately deploy the technology operationally on upcoming specific missions. We consider deployment as an instrument on NOAA's Deep Space Climate Observatory follow-on near the Sun-Earth L1 Lagrange point, as a stand-alone constellation of smallsats in low Earth orbit, or as an instrument located at the Sun-Earth L5 Lagrange point. The critical first step is the demonstration of the technology, in either a science or prototype operational mission context.

Parameters of the Geomagnetic Activity, Thermosphere, and Ionosphere for the Ultimately Intense Magnetic Storm

M. G. **Deminov**, *, A. V. Belov, E. V. Nepomnyashchaya, and V. N. Obridko

Geomagn. and Aeronomy 58 4 **2018** 501-508

http://sci-hub.tw/https://link.springer.com/article/10.1134/S0016793218040059

Equations of regression are derived for the intense magnetic storms of 1957−2016. They reflect the nonlinear relation between Dstmin and the effective index of geomagnetic activity Ap(τ) with a time-weighted factor τ. Based on this and on known estimations of the upper limit of the magnetic storm intensity (Dstmin = –2500 nT), the maximal possible value Ap(τ)max ~ 1000 nT is obtained. This makes it possible to obtain initial estimates of the upper limit of variations in some parameters of the thermosphere and ionosphere that are due to geomagnetic activity. It is found, in particular, that the upper limit of an increase in the thermospheric density is seven to eight times larger than for the storm in March 1989, which was the most intense for the entire space era. The maximum possible amplitude of the negative phase of the ionospheric storm in the number density of the F2-layer maximum at midlatitudes is nearly six times higher than for the March 1989 storm. The upper limit of the F2-layer rise in this phase of the ionospheric storm is also considerable. Based on qualitative analysis, it is found that the F2-layer maximum in daytime hours at midlatitudes for these limiting conditions is not pronounced and even may be unresolved in the experiment, i.e., above the F1-layer maximum, the electron number density may smoothly decrease with height up to the upper boundary of the plasmasphere.

Possible Influence of Extreme Magnetic Storms on the Thermosphere in the High Latitudes

Yue **Deng**, Cheng Sheng Bruce T. Tsurutani Anthony J. Mannucci

Space Weather Volume16, Issue7 July **2018** Pages 802-813

http://sci-hub.tw/10.1029/2018SW001847

Solar and interplanetary events can create extreme magnetic storms, such as the Carrington storm in 1859 with intensity up to Dst ~−1,760 nT. The influence of an idealized, smaller Carrington-type storm on the thermosphere has been simulated using the nonhydrostatic Global Ionosphere-Thermosphere Model. For the storm conditions we simulated, the solar wind BZ and velocity were −50 nT and 1,000 m/s, respectively. The corresponding cross polar cap potential reached 360 kV, and the hemispheric power was 200 GW. Consequently, the hemispheric integrated Joule heating exceeded 3,500 GW, which is more than 70 times higher than normal conditions. The thermosphere variations at high latitudes were examined through the comparison of three cases: reference, storm with geomagnetic energy enhancement only, and storm with both solar and geomagnetic energy enhancement. At 400-km altitude, the neutral density increased by >20 times at certain locations and by >10 times globally averaged. The atmosphere experienced a temperature of 4000 K, more than 1,500 m/s horizontal wind, and exceeding 150 m/s vertical wind. In general, additional energy increase from solar irradiation resulted in 20–30% more perturbation in neutral density and temperature. The exobase (top boundary of the thermosphere) expanded to altitudes >1,000 km, and the buoyancy acceleration (difference between vertical pressure gradient force and gravity force) can be as large as 3 m/s2. The results will help to determine possible extreme responses to interplanetary coronal mass ejections for various phenomena occurring in geospace.

Chapter 12 - Extreme Space Weather Events: A GOES Perspective Review

William F. **Denig**⁎DanielWilkinson⁎†Robert J.Redmon⁎

In: Extreme Events in Geospace Origins, Predictability, and Consequences **2018**, Pages 283-347

http://sci-hub.tw/10.1016/B978-0-12-812700-1.00012-1

For more than 40 years, the National Oceanic and Atmospheric Administration (NOAA) has continuously monitored the solar and near-Earth space environments in support of space weather operations. Data from this period have covered a wide range of geophysical conditions including periods of extreme space weather such as the great geomagnetic storm of Mar. 1989, the 2000 Bastille Day storm, and the 2003 Halloween storms. While not specifically addressed here, these storms have stressed our technology infrastructure in unexpected and surprising ways (see companion Chapter 24 of this volume). This chapter is focused on space weather data obtained from NOAA's Geostationary Operational Environmental Satellite (GOES) spacecraft. Signatures for extreme space weather events are in most cases readily apparent in the satellite data. Nevertheless, supporting space weather data from non-GOES sources are included in order to place the extreme cases in their overall environmental context. We present 12 cases of extreme space weather starting with the Mar. 1989 geomagnetic storm and ending with the Saint Patrick's Day storm of 2012. For each case study, an extensive literature search was performed to augment the overall discussions. **Mar. 10–15, 1989, Sep. 26–Oct. 1, 1989, Oct. 18–31, 1989, Mar. 22–28, 1991, Jun. 1–20, 1991, Jul. 14–16, 200, Nov. 4–8, 2001, 26-Oct.—06-Nov. 2003, 15-Jan.—24-Jan. 2005, 06-Sep.—16-Sep. 2005, 05-Dec.—17-Dec. 2006, 08-Mar.—17-Mar. 2012**

Table 1 Listing of extreme space weather events (1989–2012)

Book Review: Satellite Anomalies: Benefits of a Centralized Anomaly Database and Methods for Securely Sharing Information Among Satellite Operators,

Denig, W. F., R. J. Redmon, J. V. Rodriguez, and J. H. Allen

(**2014**),*Space Weather*, *12*, 528–529,

http://onlinelibrary.wiley.com/doi/10.1002/SWQv11i003/pdf

Spacecraft Charging and Mitigation

Denig, William; Cooke, David; Ferguson, Dale

Space Weather, Vol. 8, No. 10, S10007, **2010**

Satellites and spacecraft materials can become charged to tens or even thousands of volts when ions in the space environment collide with spacecraft. This can sometimes cause electrical discharge of differentially or internally charged spacecraft materials, which can adversely affect satellite operations. Additionally, high-energy ions can penetrate spacecraft materials and deposit their energy within sensitive electronics, causing component damage or failure. To consider various approaches for spacecraft charge mitigation, 150 technologists from around the world representing government, academia, and industry met at the 11th Spacecraft Charging Technology Conference (SCTC) in Albuquerque, N. M., on 20–24 September 2010. The conference was held against the backdrop of the apparent charging event of the Galaxy 15 satellite, which some speculate triggered this geosynchronous communications satellite to cease operations, thereby adversely affecting related satellite-reliant communities (see J. Allen, Space Weather, 8, S06008, doi:10.1029/2010SW000588, 2010)

An improved empirical model of electron and ion fluxes at geosynchronous orbit based on upstream solar wind conditions

M. H. **Denton**, M. G. Henderson, V. K. Jordanova, M. F. Thomsen, J. E. Borovsky, J. Woodroffe, D. P. Hartley, D. Pitchford

Space Weather **2016** DOI: 10.1002/2016SW001409

A new empirical model of the electron fluxes and ion fluxes at geosynchronous orbit (GEO) is introduced, based on observations by Los Alamos National Laboratory (LANL) satellites. The model provides flux predictions in the energy range ~1 eV to ~40 keV, as a function of local time, energy, and the strength of the solar wind electric field (the negative product of the solar wind speed and the z component of the magnetic field). Given appropriate upstream solar wind measurements, the model provides a forecast of the fluxes at GEO with a ~1 h lead time. Model predictions are tested against in-sample observations from LANL satellites and also against out-of-sample observations from the Compact Environmental Anomaly Sensor II detector on the AMC-12 satellite. The model does not reproduce all structure seen in the observations. However, for the intervals studied here (quiet and storm times) the normalized root-mean-square deviation < ~0.3. It is intended that the model will improve forecasting of the spacecraft environment at GEO and also provide improved boundary/input conditions for physical models of the magnetosphere.

Verification of space weather forecasting at the Regional Warning Center in Belgium

Andy **Devos**, Cis Verbeeck and Eva Robbrecht

J. Space Weather Space Clim. 4 (**2014**) A29

http://www.swsc-journal.org/articles/swsc/pdf/2014/01/swsc140018.pdf

The Solar Influences Data analysis Center (SIDC) in Brussels at the Royal Observatory of Belgium (ROB) has been providing daily space weather forecasts for more than a decade. A verification analysis was applied to evaluate the performance of the SIDC forecasts of fundamental space weather parameters such as the F10.7 radio flux, solar flare activity, and local geomagnetic index.

Strengths and weaknesses are determined compared to common numerical models. Descriptive model statistics, common verification measures, error analysis and conditional plots related to forecasts and observations are presented. The verification analysis methods have been designed such that future improvements and additions can easily be included, for example with new forecasting models.

The SIDC forecast (together with the persistence model) achieves the best performance for forecasting F10.7 on day 1, but has potential for improvement for a larger lead time mainly by applying estimates from the persistence and corrected recurrence models. The persistence model is superior for the forecast of flares, though corrected recurrence models are slightly better in foreseeing M- and X-class flares and the SIDC forecast estimates B- and C-class flares very well. The SIDC forecast scores better than all models in forecasting the local K-index. It best reproduces observations in the range of K = 2–4, but underestimates larger K values. The SIDC forecast provides a distribution that best matches the observations of the K-index. The analysis presented here demonstrates the influence of solar activity on the confidence level of the forecasts, as well as the hinted influence of the forecaster on duty due to the subjective nature of forecasting. The output aids to identify the strong and weak points of the SIDC forecast as well as those of the models considered. Though the presented analysis needs further extension, it already illustrates the opportunity to regularly reevaluate space weather forecasts and to stimulate ideas for improvement and increase the reliability of space weather forecasting.

THE TOTAL SOLAR IRRADIANCE CLIMATE DATA RECORD

Steven **Dewitte** and Stijn Nevens

2016 ApJ 830 25

We present the composite measurements of total solar irradiance (TSI) as measured by an ensemble of space instruments. The measurements of the individual instruments are put on a common absolute scale, and their quality is assessed by intercomparison. The composite time series is the average of all available measurements. From 1984 April to the present the TSI shows a variation in phase with the 11 yr solar cycle and no significant changes of the quiet-Sun level in between the three covered solar minima.

Deep learning reconstruction of sunspot vector magnetic fields for forecasting solar storms

Dattaraj B. **Dhuri**, Shamik Bhattacharjee, Shravan M. Hanasoge, Sashi Kiran Mahapatra

ApJ **2022**

https://arxiv.org/pdf/2209.09944.pdf

Solar magnetic activity produces extreme solar flares and coronal mass ejections, which pose grave threats to electronic infrastructure and can significantly disrupt economic activity. It is therefore important to appreciate the triggers of explosive solar activity and develop reliable space-weather forecasting. Photospheric vector-magnetic-field data capture sunspot magnetic-field complexity and can therefore improve the quality of space-weather prediction. However, state-of-the-art vector-field observations are consistently only available from Solar Dynamics Observatory/Helioseismic and Magnetic Imager (SDO/HMI) since 2010, with most other current and past missions and observational facilities such as Global Oscillations Network Group (GONG) only recording line-of-sight (LOS) fields. Here, using an inception-based convolutional neural network, we reconstruct HMI sunspot vector-field features from LOS magnetograms of HMI as well as GONG with high fidelity (~ 90% correlation) and sustained flare-forecasting accuracy. We rebuild vector-field features during the 2003 Halloween storms, for which only LOS-field observations are available, and the CNN-estimated electric-current-helicity accurately captures the observed rotation of the associated sunspot prior to the extreme flares, showing a striking increase. Our study thus paves the way for reconstructing three solar cycles worth of vector-field data from past LOS measurements, which are of great utility in improving space-weather forecasting models and gaining new insights about solar activity. **2003-10-26-31**

Relationship between Solar Energetic Particles and Properties of Flares and CMEs: Statistical Analysis of Solar Cycle 23 Events

M. **Dierckxsens**, K. Tziotziou, S. Dalla, I. Patsou, M. S. Marsh, N. B. Crosby, O. Malandraki, G. Tsiropoula

Solar Phys. March **2015**, Volume 290, Issue 3, pp 841–874
https://arxiv.org/pdf/1410.6070v2.pdf **File**
https://link.springer.com/content/pdf/10.1007%2Fs11207-014-0641-4.pdf
A statistical analysis of the relationship between solar energetic particles (SEPs) and properties of solar flares and coronal mass ejections (CMEs) is presented. SEP events during solar cycle 23 are selected which are associated with solar flares originating on the visible hemisphere of the Sun and at least of magnitude M1. Taking into account all flares and CMEs that occurred during this period, the probability for the occurrence of an SEP event near Earth is determined. A strong rise of this probability is observed for increasing flare intensities, more western locations, larger CME speeds and halo CMEs. The correlations between the proton peak flux and these solar parameters are derived for a low (>10 MeV) and high (>60 MeV) energy range excluding any flux enhancement due to the passage of fast interplanetary shocks. The obtained correlation coefficients are: 0.55+-0.07 (0.63+-0.06) with flare intensity and 0.56+-0.08 (0.40+-0.09) with the CME speed for E>10 MeV (E>60 MeV). For both energy ranges, the correlations with flare longitude and CME width are very small or non-existent. Furthermore, the occurrence probabilities, correlation coefficients and mean peak fluxes are derived in multi-dimensional bins combining the aforementioned solar parameters. The correlation coefficients are also determined in different proton energy channels ranging from 5 to 200 MeV. The results show that the correlation between the proton peak flux and the CME speed decreases with energy, while the correlation with the flare intensity shows the opposite behavior. Furthermore, the correlation with the CME speed is stronger than the correlation with the flare intensity below 15 MeV and becomes weaker above 20 MeV. Excluding the flux enhancements due to interplanetary shocks, only a small but not very significant change is observed in the correlation between the peak flux below 7 MeV and the CME speed. **Tables**

Specifying Satellite Drag Through Coupled Thermosphere-Ionosphere Data Assimilation of Radio Occultation Electron Density Profiles

Nicholas **Dietrich**, Tomoko Matsuo, Chih-Ting Hsu
Space Weather e2022SW003147 **Volume20, Issue8** **2022**
https://doi.org/10.1029/2022SW003147
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022SW003147
The largest obstacle to managing satellites in low Earth orbit (LEO) is accurately forecasting the neutral mass densities that appreciably impact atmospheric drag. Empirical thermospheric models are often used to estimate neutral densities but they struggle to forecast neutral densities during geomagnetic storms when they are highly variable. Physics-based models are thus increasingly turned to for their ability to describe the dynamical evolution of neutral densities. However, these models require observations to constrain dynamical state variables to be able to forecast mass densities with adequate fidelity. The LEO environment has scarce neutral state observations. Here we demonstrate in simulated experiments a reduction in orbit errors and neutral densities using a physics-based, data assimilation approach with ionospheric observations. Using a coupled thermosphere-ionosphere (T-I) model, the Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM), we assimilate COSMIC electron density profiles (EDPs) derived from radio occultation (RO) observations. We use the EDPs to directly-update neutral states, improving errors for neutral temperature by 70% and neutral winds by 20%. Updated neutral temperature and neutral winds additionally improve helium composition errors by 60% and 40%, respectively. Improved neutral density estimates correspond to a reduction in orbit errors of 1.2 km over 2 days, a 70% reduction over a no-assimilation control, and a 29 km improvement over 9 days. This study builds on the results of our earlier work to further develop and demonstrate the potential of using a vast and growing RO data source, with a physics-based model, to overcome our limited number of neutral observations.

Simulating Properties of “Seasonal” Variability in Solar Activity And Space Weather Impacts

Mausumi **Dikpati,** Scott McIntosh, and Simon Wing
Front. Astron. Space Sci., 11 May **2021** |
https://doi.org/10.3389/fspas.2021.688604
https://www.frontiersin.org/articles/10.3389/fspas.2021.688604/full
Solar short-term, quasi-annual variability within a decadal sunspot-cycle has recently been observed to strongly correlate with major class solar flares, resulting into quasi-periodic space weather “seasons.” In search for the origin of this quasi-periodic enhanced activity bursts, significant researches are going on. In this article we show, by employing a 3D thin-shell shallow-water type model, that magnetically modified Rossby waves can interact with spot-producing toroidal fields and create certain quasi-periodic spatio-temporal patterns, which plausibly cause a season of enhanced solar activity followed by a relatively quiet period. This is analogous to the Earth’s lower atmosphere, where Rossby waves and jet streams are produced and drive global terrestrial weather. Shallow-water models have been applied to study terrestrial Rossby waves, because their generation layer in the Earth’s lower atmospheric region has a much larger horizontal than vertical scale, one of the model-requirements. In the Sun, though Rossby waves can be generated at various locations, particularly favorable locations are the subadiabatic

layers at/near the base of the convection zone where the horizontal scale of the fluid and disturbances in it can be much larger than the vertical scale. However, one important difference with respect to terrestrial waves is that solar Rossby waves are magnetically modified due to presence of strong magnetic fields in the Sun. We consider plausible magnetic field configurations at the base of the convection zone during different phases of the cycle and describe the properties of energetically active Rossby waves generated in our model. We also discuss their influence in causing short-term spatio-temporal variability in solar activity and how this variability could have space weather impacts. An example of a possible space weather impact on the Earth's radiation belts are presented.

Modeling the Geomagnetic Response to the September 2017 Space Weather Event Over Fennoscandia Using the Space Weather Modeling Framework: Studying the Impacts of Spatial Resolution

A. P. **Dimmock**, D. T. Welling, L. Rosenqvist, C. Forsyth, M. P. Freeman, I. J. Rae, A. Viljanen, E. Vandegriff, R. J. Boynton, M. A. Balikhin, E. Yordanova

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https://doi.org/10.1029/2020SW002683

We must be able to predict and mitigate against geomagnetically induced current (GIC) effects to minimize socio-economic impacts. This study employs the space weather modeling framework (SWMF) to model the geomagnetic response over Fennoscandia to the September 7–8, 2017 event. Of key importance to this study is the effects of spatial resolution in terms of regional forecasts and improved GIC modeling results. Therefore, we ran the model at comparatively low, medium, and high spatial resolutions. The virtual magnetometers from each model run are compared with observations from the IMAGE magnetometer network across various latitudes and over regional-scales. The virtual magnetometer data from the SWMF are coupled with a local ground conductivity model which is used to calculate the geoelectric field and estimate GICs in a Finnish natural gas pipeline. This investigation has lead to several important results in which higher resolution yielded: (1) more realistic amplitudes and timings of GICs, (2) higher amplitude geomagnetic disturbances across latitudes, and (3) increased regional variations in terms of differences between stations. Despite this, substorms remain a significant challenge to surface magnetic field prediction from global magnetohydrodynamic modeling. For example, in the presence of multiple large substorms, the associated large-amplitude depressions were not captured, which caused the largest model-data deviations. The results from this work are of key importance to both modelers and space weather operators. Particularly when the goal is to obtain improved regional forecasts of geomagnetic disturbances and/or more realistic estimates of the geoelectric field. **7-8 Sep 2017**

Beating 1 Sievert: Optimal Radiation Shielding of Astronauts on a Mission to Mars

M.I. **Dobynde**, Y.Y. Shprits, A.Yu. Drozdov, J. Hoffman, J. Li

Space Weather e2021SW002749 **2021**

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https://doi.org/10.1029/2021SW002749

Space radiation is one of the main concerns in planning long-term human space missions. There are two main types of hazardous radiation: Solar Energetic Particles (SEP) and Galactic Cosmic Rays (GCR). The intensity and evolution of both depends on solar activity. GCR activity is most enhanced during solar minimum and lowest during solar maximum. SEP probability and intensity are maximized during solar maximum and are minimized during solar minimum. In this study, we combine models of the particle environment arising due to SEP and GCR with Monte-Carlo simulations of radiation propagation inside a spacecraft and phantom. We include 28 fully ionized GCR elements from hydrogen to nickel and consider protons and nine ion species to model the SEP irradiation. Our calculations demonstrate that the optimal time for a flight to Mars is during solar maximum, and that the flight duration should not exceed approximately 4 years.

Deep Learning for Space Weather Prediction: Bridging the Gap between Heliophysics Data and Theory

John C. **Dorelli**, Chris Bard, Thomas Y. Chen, +++

Heliophysics 2050 White Paper **2022**

https://arxiv.org/ftp/arxiv/papers/2212/2212.13328.pdf

Traditionally, data analysis and theory have been viewed as separate disciplines, each feeding into fundamentally different types of models. Modern deep learning technology is beginning to unify these two disciplines and will produce a new class of predictively powerful space weather models that combine the physical insights gained by data and theory. We call on NASA to invest in the research and infrastructure necessary for the heliophysics' community to take advantage of these advances.

Space Weather and Satellite Anomalies

Dorman, Lev; Iucci, N.; Levitin, A. E.; Belov, A. V.; Eroshenko, E. A.; Ptitsyna, N. G.; Villoresi, G.; Chizhenkov, G. V.; Gromova, L. I.; Parisi, M.; and 2 coauthors

38th COSPAR Scientific Assembly. Held 18-15 July **2010**, in Bremen, Germany, p.2

Results of the Satellite Anomaly Project, which aims to improve the methods of safeguarding satellites in the Earth's magnetosphere from the negative effects of the space environment, are presented. Anomaly data from the "Kosmos" series satellites in the period 1971-1999 are combined in one database, together with similar information on other spacecrafts. This database contains, beyond the anomaly information, various characteristics of the space weather: geo-magnetic activity indices (Ap, AE and Dst), fluxes and fluencies of electrons and protons at different energies, high energy cosmic ray variations and other solar, interplanetary and solar wind data. A comparative analysis of the distribution of each of these parameters relative to satellite anomalies was carried out for the total number of anomalies (about 6000 events), and separately for high (5000 events) and low (about 800 events) altitude orbit satellites. No relation was found between low and high altitude satellite anomalies. Daily numbers of satellite anomalies, averaged by a superposed epoch method around sudden storm commencements and proton event onsets for high (~1500 km) and low (¡1500 km) altitude orbits revealed a big difference in a behavior. Satellites were divided on several groups according to the orbital characteristics (altitude and inclination). The relation of satellite anomalies to the environmental parameters was found to be different for various orbits that should be taken into account under developing of the anomaly frequency models. The preliminary anomaly frequency models are presented.

Space weather and dangerous phenomena on the Earth: principles of great geomagnetic storms forcasting by online cosmic ray data

L. I. **Dorman**

ANGEO - Volume 23, Number 9, **2005**, Page(s) 2997-3002

Abstract   Full Article (PDF, 700 KB)   Special Issue

Space weather and space anomalies

L. I. **Dorman,** N. Iucci, A. V. Belov, A. E. Levitin, E. A. Eroshenko, N. G. Ptitsyna, G. Villoresi, G. V. Chizhenkov, L. I. Gromova, M. Parisi, M. I. Tyasto, and V. G. Yanke

ANGEO - Volume 23, Number 9, **2005**, Page(s) 3009-3018

Abstract   Full Article (PDF, 189 KB)   Special Issue

A large database of anomalies, registered by 220 satellites in different orbits over the period 1971–1994 has been compiled. For the first time, data from 49 Russian Kosmos satellites have been included in a statistical analysis. The database also contains a large set of daily and hourly space weather parameters. A series of statistical analyses made it possible to quantify, for different satellite orbits, space weather conditions on the days characterized by anomaly occurrences. In particular, very intense fluxes (>1000 pfu at energy >10MeV) of solar protons are linked to anomalies registered by satellites in high-altitude (>15 000 km), near-polar (inclination >55_) orbits typical for navigation satellites, such as those used in the GPS network, NAVSTAR, etc. (the rate of anomalies increases by a factor _20), and to a much smaller extent to anomalies in geostationary orbits, (they increase by a factor _4). Direct and indirect connections between anomaly occurrence and geomagnetic perturbations are also discussed.

Nitrate ions spikes in ice cores are not suitable proxies for solar proton events

Katharine A. **Duderstadt**, Jack E. Dibb, Charles H. Jackman, Cora E. Randall, Nathan A. Schwadron, Stanley C. Solomon, Harlan E. Spence, Valery A. Yudin

Journal of Geophysical Research: Atmospheres   **201**5

http://arxiv.org/pdf/1511.03358v1.pdf

Nitrate ion spikes in polar ice cores are contentiously used to estimate the intensity, frequency, and probability of historical solar proton events, quantities that are needed to prepare for potentially society-crippling space weather events. We use the Whole Atmosphere Community Climate Model to calculate how large an event would have to be to produce enough odd nitrogen throughout the atmosphere to be discernible as nitrate peaks at the Earth's surface. These hypothetically large events are compared with probability of occurrence estimates derived from measured events, sunspot records, and cosmogenic radionuclides archives. We conclude that the fluence and spectrum of solar proton events necessary to produce odd nitrogen enhancements equivalent to the spikes of nitrate ions in Greenland ice cores are unlikely to have occurred throughout the Holocene, confirming that nitrate ions in ice cores are not suitable proxies for historical individual solar proton events.

The Vigil Magnetometer for Operational Space Weather Services From the Sun-Earth L5 Point

J. P. **Eastwood**, P. Brown, W. Magnes, C. M. Carr, M. Agu, R. Baughen, G. Berghofer, J. Hodgkins, I. Jernej, C. Möstl, T. Oddy, A. Strickland, A. Vitkova

Space Weather Volume22, Issue6 June **2024** e2024SW003867
https://doi.org/10.1029/2024SW003867
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2024SW003867
Severe space weather has the potential to cause significant socio-economic impact and it is widely accepted that mitigating this risk requires more comprehensive observations of the Sun and heliosphere, enabling more accurate forecasting of significant events with longer lead-times. In this context, it is now recognized that observations from the L5 Sun-Earth Lagrange point (both remote and in situ) would offer considerable improvements in our ability to monitor and forecast space weather. Remote sensing from L5 allows for the observation of solar features earlier than at L1, providing early monitoring of active region development, as well as tracking of interplanetary coronal mass ejections through the inner heliosphere. In situ measurements at L5 characterize the solar wind's geoeffectiveness (particularly stream interaction regions), and can also be ingested into heliospheric models, improving their performance. The Vigil space weather mission is part of the ESA Space Safety Program and will provide a real-time data stream for space weather services from L5 following its anticipated launch in the early 2030s. The interplanetary magnetic field is a key observational parameter, and here we describe the development of the Vigil magnetometer instrument for operational space weather monitoring at the L5 point. We summarize the baseline instrument capabilities, demonstrating how heritage from science missions has been leveraged to develop a low-risk, high-heritage instrument concept.

Quantifying the Economic Value of Space Weather Forecasting for Power Grids: An Exploratory Study **Review**

J. P. **Eastwood** , M. A. Hapgood , E. Biffis , D. Benedetti, M. M. Bisi , L. Green , R. D. Bentley , C. Burnett
Space Weather 16?, 12 2052-2067 **2018**
sci-hub.tw/10.1029/2018SW002003
Space Weather Quarterly Vol. 15, Issue 4, **2018**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/swq.20
An accurate understanding of space weather socioeconomic impact is fundamental to the development of appropriate operational services, forecasting capabilities, and mitigation strategies. One way to approach this problem is by developing physics-based models and frameworks that can lead to a bottom-up estimate of risk and likely impact. Here we describe the development of a new framework to assess the economic impact of space weather on power distribution networks and the supply of electricity. In particular, we focus on the phenomenon of the geomagnetic substorm, which is relatively localized in time and space, and occurs multiple times with varying severity during a geomagnetic storm. The framework uses the AE index to characterize substorm severity, and the impact of the substorm is modulated by the resilience of the power grid and the nature of available forecast. Possible scenarios for substorm sequences during a 1-in-10-, a 1-in-30-, and a 1-in-100-year geomagnetic storm events are generated based on the 2003, 1989, and 1859 geomagnetic storms. Economic impact, including international spill over, can then be calculated using standard techniques, based on the duration and the geographical footprint of the power outage. Illustrative calculations are made for the European sector, for a variety of forecast and resilience scenarios. However, currently available data are highly regionally inhomogeneous, frustrating attempts to define an overall global economic impact at the present time.

The economic impact of space weather: Where do we stand? **Review**

Eastwood, J.P., Biffis, E., Hapgood, M.A., Green, L., Bisi, M.M., Bentley, R.D.,Wicks, R., McKinnell, L.A., Gibbs, M., Burnett, C.:
2017, Risk Anal. 37(2), 206.
https://onlinelibrary.wiley.com/doi/epdf/10.1111/risa.12765
Space weather describes the way in which the Sun, and conditions in space more generally, impact human activity and technology both in space and on the ground. It is now well understood that space weather represents a significant threat to infrastructure resilience, and is a source of risk that is wide-ranging in its impact and the pathways by which this impact may occur. Although space weather is growing rapidly as a field, work rigorously assessing the overall economic cost of space weather appears to be in its infancy. Here, we provide an initial literature review to gather and assess the quality of any published assessments of space weather impacts and socioeconomic studies. Generally speaking, there is a good volume of scientific peer-reviewed literature detailing the likelihood and statistics of different types of space weather phenomena. These phenomena all typically exhibit "power-law" behavior in their severity. The literature on documented impacts is not as extensive, with many case studies, but few statistical studies. The literature on the economic impacts of space weather is rather sparse and not as well developed when compared to the other sections, most probably due to the somewhat limited data that are available from end-users. The major risk is attached to power distribution systems and there is disagreement as to the severity of the technological footprint. This strongly controls the economic impact. Consequently, urgent work is required to better quantify the risk of future space weather events.

The Scientific Foundations of Forecasting Magnetospheric Space Weather Review

J. P. **Eastwood**, R. Nakamura, L. Turc, L. Mejnertsen, M. Hesse

Space Science Reviews Volume 212, Issue 3–4, pp 1221–1252 **2017**
https://link.springer.com/content/pdf/10.1007%2Fs11214-017-0399-8.pdf

The magnetosphere is the lens through which solar space weather phenomena are focused and directed towards the Earth. In particular, the non-linear interaction of the solar wind with the Earth's magnetic field leads to the formation of highly inhomogenous electrical currents in the ionosphere which can ultimately result in damage to and problems with the operation of power distribution networks. Since electric power is the fundamental cornerstone of modern life, the interruption of power is the primary pathway by which space weather has impact on human activity and technology. Consequently, in the context of space weather, it is the ability to predict geomagnetic activity that is of key importance. This is usually stated in terms of geomagnetic storms, but we argue that in fact it is the substorm phenomenon which contains the crucial physics, and therefore prediction of substorm occurrence, severity and duration, either within the context of a longer-lasting geomagnetic storm, but potentially also as an isolated event, is of critical importance. Here we review the physics of the magnetosphere in the frame of space weather forecasting, focusing on recent results, current understanding, and an assessment of probable future developments.

Is climate variability the result of frequency modulation by the solar cycle? Evidence from the El Nino Southern Oscillation, Australian climate, Central England Temperature, and reconstructed solar activity and climate records

Ian R. **Edmonds**

2024
https://arxiv.org/pdf/2404.13542.pdf

Oceanic atmospheric oscillations and climate variability are tightly linked and both exhibit broad band spectral content that ranges, with roughly equal strength, from annual to centennial periodicity. The explanation for variability based on the integration of weather noise leads to a spectral content heavily weighted to low frequencies; explaining the variability as resulting from solar forcing leads to a narrow band, approximately eleven year period, spectral content. In both cases the spectral content is incompatible with the observed spectrum. It is known that the Southern Oscillation is frequency modulated, i.e. the time interval between successive events varies on an approximately centenary scale. In this paper we develop a model of the Southern Oscillation responding to the slowly changing frequency of the solar cycle. This results in a frequency modulated oscillation, the spectrum of which is intrinsically broad and flat and therefore compatible with the observed spectrum. Fortunately, the change in frequency of the solar cycle with time has been reconstructed from tree ring data for the last millennium. It is possible to identify time intervals when the frequency was dominated by a single frequency in which case the model oscillation is relatively simple. The 11 year period component of the model time variation was shown to correlate closely with the 11 year period components of observed Southern Oscillation and climate variability. A characteristic of a frequency modulated variable, the equal spacing of spectral peaks, was utilized via a double Fourier transform method to recover solar cycle periodicity from instrumental and reconstructed climate records, with the recovered periodicity and the known periodicity of the solar cycle in good agreement. The concept outlined provides a new way of viewing and assessing the Sun climate connection.

Ensemble forecasting of coronal mass ejections using the WSA-ENLIL with CONED Model

D. **Emmons**1,2,*, A. Acebal, A. Pulkkinen, 3,4, A. Taktakishvili, P. MacNeice3, D. Odstrcil

Space Weather, Volume 11, Issue 3, pages 95–106, March **2013**

The combination of the Wang-Sheeley-Arge (WSA) coronal model, ENLIL heliospherical model version 2.7, and CONED Model version 1.3 (WSA-ENLIL with CONED Model) was employed to form ensemble forecasts for 15 halo coronal mass ejections (halo CMEs). The input parameter distributions were formed from 100 sets of CME cone parameters derived from the CONED Model. The CONED Model used image processing along with the bootstrap approach to automatically calculate cone parameter distributions from SOHO/LASCO imagery based on techniques described by Pulkkinen et al. (2010). The input parameter distributions were used as input to WSA-ENLIL to calculate the temporal evolution of the CMEs, which were analyzed to determine the propagation times to the L1 Lagrangian point and the maximum Kp indices due to the impact of the CMEs on the Earth's magnetosphere. The Newell et al. (2007) Kp index formula was employed to calculate the maximum Kp indices based on the predicted solar wind parameters near Earth assuming two magnetic field orientations: a completely southward magnetic field and a uniformly distributed clock-angle in the Newell et al. (2007) Kp index formula. The forecasts for 5 of the 15 events had accuracy such that the actual propagation time was within the ensemble average plus or minus one standard deviation. Using the completely southward magnetic field assumption, 10 of the 15 events contained the actual maximum Kp index within the range of the ensemble forecast, compared to 9 of the 15 events when using a uniformly distributed clock angle.

The future of ground magnetometer arrays in support of space weather monitoring and research.

Engebretson, M., & Zesta, E.
(**2017**). Space Weather (Quarterly), 15, No. 4, 1433–1441.
http://onlinelibrary.wiley.com/doi/10.1002/swq.16/epdf

SPRINTS: A Framework for Solar-Driven Event Forecasting and Research

A. J. **Engell**, D. A. Falconer, M. Schuh, J. Loomis, D. Bissett
Space Weather Volume 15, Issue 10 October **2017** Pages 1321–1346
http://sci-hub.cc/10.1002/2017SW001660

Capabilities to predict onset and time profiles of solar-driven events, including solar X-ray flares; solar energetic particles (SEP); coronal mass ejections; and high-speed streams, are critical in mitigating their potential impacts. We introduce the Space Radiation Intelligence System (SPRINTS). This NASA-invested technology integrates preeruptive metadata and forecasts from the MAG4 system with posteruptive metadata in order to produce high fidelity and preeruptive to posteruptive transitional forecasts for solar-driven events. To catalog start and end times of the four solar-driven events, SPRINTS is capable of generating posteruptive forecasts based on automatic detections employed on 30+ years of GOES X-ray and particle data as well as 20+ years of ACE and DSCOVR solar wind data. The prediction results for 1986–2016 presented here are from the SPRINTS posteruptive capability for forecasting SEPs leveraging GOES X-ray metadata. We present onset, peak flux, and time profile SEP forecast metrics and results based on expert-guided, statistical, and machine-learned decision tree models. Operating on data from a 20 year period, a machine-learned decision tree model provided the best results for predicting an S1 event (on the NOAA Space Weather Prediction Center Solar Radiation Scale): 86% probability of detection and 37% false alarm rate. Five flare-related metadata sets were leveraged in the decision tree modeling. Consistently, flare-integrated flux, flare heliolongitude, and flare decay-phase duration were found to be the top three forecasting parameters, while flare magnitude and flare latitude had little to no impact on the SEP forecast model. For the solar-driven events of March 2012, we demonstrate SPRINTS abilities to forecast solar flares, SEP onset, and SEP evolution. **16 Aug 2001, 25 Aug 2001, 28 October 2003, 7 March 2012**

Extreme Space Weather Impacts on GNSS Timing Signals for Electricity Grid Management

T. Etchells, K. L. Aplin, L. Berthoud, A. Kalavana, A. Larkins
Space Weather Volume22, Issue10 October **2024** e2023SW003770
https://doi.org/10.1029/2023SW003770
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2023SW003770

Extreme space weather events can have serious impacts on critical infrastructure, including Global Navigation Satellite Systems (GNSS). The use of GNSS, particularly as sources of accurate timing signals, is becoming more widespread, with one example being the measurement of electricity grid frequency and phase information to aid grid management and stability. Understanding the likelihood of extreme space weather impacts on GNSS timing signals is therefore becoming vital to maintain national electricity grid resilience. This study determines critical intensity thresholds above which the complete failure of a GNSS based timing system may occur. Solar radio bursts are identified as a simple example to investigate in more detail. The probability of occurrence of an extreme space weather event with an intensity equal to or greater than the critical intensity is estimated. Both a power law and extreme value theory were used to evaluate recurrence probabilities based on historical event frequencies. The probability was estimated to be between 3%–12% per decade to cause the complete failure of any GNSS-based timing system.

Solar flare forecasting using morphological properties of sunspot groups

M. **Falco**, P. Costa, P. Romano
Journal of Space Weather and Space Climate **2019**
https://arxiv.org/pdf/1905.05759.pdf

We describe a new tool developed for solar flare forecasting on the base of some sunspot group properties. Assuming that the flare frequency follows the Poisson statistics, this tool uses a database containing the morphological characteristics of the suspot groups daily observed by the Equatorial Spar of INAF − Catania Astrophysical Observatory since January 2002 up today. By means of a linear combination of the flare rates computed on the base of some properties of the sunspot groups, like area, number of pores and sunspots, Zurich class, relative importance between leading spot and density of the sunspot population, and type of penumbra of the main sunspot, we determine the probability percentages that a flare of a particular energy range may occur. Comparing our forecasts with the flares registered by GOES satellites in the 1−8 \AA{} X−ray band during the subsequent 24 hrs we measured the performance of our method. We found that this method, which combines some morphological parameters and a statistical technique, has the best performances for the strongest events, which are more interesting for their implications in the Earth environment. **6-7 Sept 2017**

MAG4 versus alternative techniques for forecasting active region flare productivity

David A. **Falconer**, Ronald L. Moore, Abdulnasser F. Barghouty and Igor Khazanov

Space Weather, Volume 12, Issue 5, pages 306–317, **2014 File**

http://sci-hub.tw/10.1002/2013SW001024

MAG4 is a technique of forecasting an active region's rate of production of major flares in the coming few days from a free magnetic energy proxy. We present a statistical method of measuring the difference in performance between MAG4 and comparable alternative techniques that forecast an active region's major-flare productivity from alternative observed aspects of the active region. We demonstrate the method by measuring the difference in performance between the “Present MAG4” technique and each of three alternative techniques, called “McIntosh Active-Region Class,” “Total Magnetic Flux,” and “Next MAG4.” We do this by using (1) the MAG4 database of magnetograms and major flare histories of sunspot active regions, (2) the NOAA table of the major-flare productivity of each of 60 McIntosh active-region classes of sunspot active regions, and (3) five technique performance metrics (Heidke Skill Score, True Skill Score, Percent Correct, Probability of Detection, and False Alarm Rate) evaluated from 2000 random two-by-two contingency tables obtained from the databases. We find that (1) Present MAG4 far outperforms both McIntosh Active-Region Class and Total Magnetic Flux, (2) Next MAG4 significantly outperforms Present MAG4, (3) the performance of Next MAG4 is insensitive to the forward and backward temporal windows used, in the range of one to a few days, and (4) forecasting from the free-energy proxy in combination with either any broad category of McIntosh active-region classes or any Mount Wilson active-region class gives no significant performance improvement over forecasting from the free-energy proxy alone (Present MAG4).

See Falconer_presentation, **2014**

A tool for empirical forecasting of major flares, coronal mass ejections, and solar particle events from a proxy of active-region free magnetic energy

Falconer, David; Barghouty, Abdulnasser F.; Khazanov, Igor; Moore, Ron

Space Weather, Vol. 9, No. 4, S04003, **2011, File**

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2009SW000537

This paper describes a new forecasting tool developed for and currently being tested by NASA's Space Radiation Analysis Group (SRAG) at Johnson Space Center, which is responsible for the monitoring and forecasting of radiation exposure levels of astronauts. The new software tool is designed for the empirical forecasting of M- and X-class flares, coronal mass ejections, and solar energetic particle events. For each type of event, the algorithm is based on the empirical relationship between the event rate and a proxy of the active region's free magnetic energy. Each empirical relationship is determined from a data set of ∼40,000 active-region magnetograms from ∼1300 active regions observed by SOHO/Michelson Doppler Imager (MDI) that have known histories of flare, coronal mass ejection, and solar energetic particle event production. The new tool automatically extracts each strong-field magnetic area from an MDI full-disk magnetogram, identifies each as a NOAA active region, and measures the proxy of the active region's free magnetic energy from the extracted magnetogram. For each active region, the empirical relationship is then used to convert the free-magnetic-energy proxy into an expected event rate. The expected event rate in turn can be readily converted into the probability that the active region will produce such an event in a given forward time window. Descriptions of the data sets, algorithm, and software in addition to sample applications and a validation test are presented. Further development and transition of the new tool in anticipation of SDO/HMI are briefly discussed.

Correlation Analysis on Solar Activity with Cosmic Radiation Event Based on HiSPARC

Ke-zhou **Fan**, Jaap Velthuis

2018

https://arxiv.org/ftp/arxiv/papers/1808/1808.10645.pdf

In this paper, we analyze the influence of characteristic solar activity parameters as well as the joint effect of solar activity and atmospheric pressure on the records of cosmic radiation based on HiSPARC, a ground-based detector monitoring secondary cosmic ray intensity. We gather the data from No.501 HiSPARC station situated at Nikhef in Science Park, Amsterdam, Netherlands (52.3558963{\deg}N, 4.9509827{\deg}E, 56.18 m of altitude). From the anticorrelation between the number of solar flares, relative number of sunspots and that of events, we attain the function expression by employing an exponential fitting model. Furthermore, we quantitatively find the correlation between the daily average number of cosmic ray events and the characteristic solar activity parameters, including the number, the area and the latitude of sunspot groups within one month. Meanwhile, turning to the analysis on the joint effect, we calculate the turning interval, beyond which the influence of solar activity on the number of events is weaker than atmospheric pressure.

Space Weather Environment During the SpaceX Starlink Satellite Loss in February 2022
Tzu-Wei **Fang**, Adam Kubaryk, David Goldstein, Zhuxiao Li, Tim Fuller-Rowell, George Millward, Howard J. Singer, Robert Steenburgh, Solomon Westerman, Erik Babcock
Space Weather e2022SW003193 **Volume20, Issue11** **2022**
https://doi.org/10.1029/2022SW003193
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022SW003193
On **3 February 2022**, SpaceX Starlink launched and subsequently lost 38 of 49 satellites due to enhanced neutral density associated with a geomagnetic storm. This study examines the space weather conditions related to the satellite loss, based on observations, forecasts, and numerical simulations from the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC). Working closely with the Starlink team, the thermospheric densities along the satellite orbits were estimated and the neutral density increase leading to the satellite loss was investigated. Simulation results suggest that during the geomagnetic storm, pre-launch Monte Carlo analyses performed by the Starlink team using empirical neutral density inputs from NRLMSISE-00 tended to underestimate the impact relative to predictions from the operational WAM-IPE physics-based model. The numerical simulation indicated this minor to moderate geomagnetic storm was sufficient to create 50% to 125% density enhancement at altitudes ranging between 200 km and 400 km. With the increasing solar activity of Solar Cycle 25, satellites in low-Earth orbit (LEO) are expected to experience an increasing number of thermospheric expansion events. Currently, no alerts and warnings issued by SWPC are focused on satellite users concerned with atmospheric drag and related applications. Thus, during geomagnetic storms, it is crucial to establish suitable alerts and warnings based on neutral density predictions to provide users guidance for preventing satellite losses due to drag and to aid in collision avoidance calculations.

Space Weather Related to Solar Eruptions With the ASO-S Mission **As a Review**
Li **Feng**1,2*, Weiqun Gan1,2, Siqing Liu3, Huaning Wang4, Hui Li1,2, et al.
Front. Phys., 11 March **2020** | https://doi.org/10.3389/fphy.2020.00045 **File**
sci-hub.si/10.3389/fphy.2020.00045
The Advanced Space-based Solar Observatory (ASO-S) is a mission aiming at exploring solar flares, coronal mass ejections (CMEs), solar magnetic field and their relationships. To fulfill its major scientific objectives, ASO-S has three elaborately-designed payloads onboard: the Full-disk vector MagnetoGraph (FMG), the Lyman-alpha Solar Telescope (LST), and the Hard X-ray Imager (HXI) dedicated to observe vector magnetic fields, CMEs, and flares, respectively. Beside the scientific objectives, we have an operational objective to observe solar eruptions and magnetic field for making related space weather forecasts. More specifically, we have set a priority for the downlink of CME data observed by LST, and will distribute those data to different space weather prediction centers in China within 2 h once the Science Operation and Data Center (SODC) of ASO-S receive the data. After data downlink and archiving, different automatic detection, tracking, and cataloging procedures are planned to run for the most critical solar eruptive features. On the other hand, based on the distributed and downloaded data, different space weather prediction centers are to activate their forecast systems for the ASO-S observed solar eruption events. Our particular interests are currently focused on nowcast of different eruption events, prediction of CME arrivals, forecast of solar flares and the onset of solar eruptions. We are also working on further forecast potentials using the ASO-S data to make contributions to other possible important issues of space weather.

Occurrence rate and duration of space weather impacts on high-frequency radio communication used by aviation
Robyn A. D. **Fiori,** Vickal V. Kumar, David H. Boteler and Michael B. Terkildsen
J. Space Weather Space Clim. **2022**, 12, 21
https://www.swsc-journal.org/articles/swsc/pdf/2022/01/swsc220003.pdf
High frequency (HF) radio wave propagation is sensitive to space weather-induced ionospheric disturbances that result from enhanced photoionization and energetic particle precipitation. Recognizing the potential risk to HF radio communication systems used by the aviation industry, as well as potential impacts on GNSS navigation and the risk of elevated radiation levels, the International Civil Aviation Organization (ICAO) initiated the development of a space weather advisory service. For HF systems, this service specifically identifies shortwave fadeout, auroral absorption, polar cap absorption, and post-storm maximum useable frequency depression (PSD) as phenomena impacting HF radio communication and specifies moderate and severe event thresholds to describe event severity. This paper examines the occurrence rate and duration of events crossing the moderate and severe thresholds. Shortwave fadeout was evaluated based on thresholds in the solar X-ray flux. Analysis of 40-years of solar X-ray flux data showed that moderate and severe level solar X-ray flares were observed, on average, 123 and 5 times per 11-year solar cycle, respectively. The mean event duration was 68 min for moderate level events and 132 min for severe level events. Auroral absorption events crossed the moderate threshold for 40 events per solar cycle, with a mean event duration of 5.1 h. The severe threshold was crossed for 3 events per solar cycle with a mean event

duration of 12 h. Polar cap absorption had the longest mean duration at ~8 h for moderate events and 1.6 days for severe events; on average, 24 moderate and 13 severe events were observed per solar cycle. Moderate and severe thresholds for shortwave fadeout, auroral absorption, and polar cap absorption were used to determine the expected impacts on HF radio communication. Results for polar cap absorption and shortwave fadeout were consistent with each other, but the expected impact for auroral absorption was shown to be 2–3 times higher. Analysis of 22 years of ionosonde data showed moderate, and severe PSD events occurred, on average, 200 and 56 times per 11-year solar cycle, respectively. The mean event duration was 5.5 h for moderate-level events and 8.5 h for severe-level events. During solar cycles 22 and 23, HF radio communication was expected to experience moderate or severe impacts due to the ionospheric disturbances caused by space weather, a maximum of 163 and 78 days per year, respectively, due to the combined effect of absorption and PSD. The distribution of events is highly non-uniform with respect to the solar cycle: 70% of moderate or severe events were observed during solar maximum compared to solar minimum.

Examining the Potential of the Super Dual Auroral Radar Network for Monitoring the Space Weather Impact of Solar X-Ray Flares

R. A. D. **Fiori**, A. V. Koustov, S. Chakraborty, J. M. Ruohoniemi, D. W. Danskin, D. H. Boteler, S. G. Shepherd

Space Weather Volume16, Issue9 September **2018** Pages 1348-1362
sci-hub.tw/10.1029/2018SW001905

Increased electron density in the ionosphere due to photoionization by radiation emitted during a solar X-ray flare impacts high-frequency (HF) radio wave propagation. Shortwave fadeout (SWF) due to the enhanced D region absorption that results is characterized by the level of cosmic radio noise attenuation derived from riometer measurements. SWF impacts HF radio propagation and has been identified in the Super Dual Auroral Radar Network (SuperDARN) data. An X2.1 solar X-ray flare that erupted on 11 March 2015 is examined to determine its effects on HF radio propagation. Riometer data indicate a sharp enhancement in absorption, which falls off with increasing solar zenith angle. SuperDARN radars observed a suppression of both ground scatter and ionospheric echoes. Ground scatter data indicated a rapid weakening of signal from far to near ranges followed by a ~20-min interval of complete signal loss. Recovery lasted ~30 min and proceeded from near to far ranges. Prior to the complete signal loss, an apparent sharp velocity impulse (Doppler flash) lasting 1–2 min was observed in the ground scatter data. The peak of this flash preceded the onset of enhanced absorption. The onset of signal loss by SuperDARN preceded the onset of enhanced absorption observed by riometers. Both data sets observed a positive correlation between increasing delay in onset and increasing solar zenith angle with onset progressing at an average rate of 16.7°/min (0.060 min/°). Agreement between riometer and SuperDARN indicates the possibility of using a joint data set for improved monitoring of the space weather impact of solar X-ray flares.

National Space Weather Portal Is Online,

Fisher, G. and M. Bonadonna

Space Weather, 10, S07006, (**2012**), doi:10.1029/2012SW000831.

The Unified National Space Weather Portal provides a gateway to access federally funded space weather information, services, and activities. It connects to a system of existing portals and websites, providing national information to enhance understanding.
This portal was developed through the National Space Weather Program (NSWP) as part of the Unified National Space Weather Capability. The NSWP is an interagency initiative to speed improvement in space weather services and prepare the country to deal with technological vulnerabilities associated with the space environment.

See http://www.spaceweather.gov/portal

Building resilience of the Global Positioning System to space weather

Fisher, Genene; Kunches, Joseph

Space Weather, Vol. 9, No. 12, S12004, **2011**
http://dx.doi.org/10.1029/2011SW000718

A recent report by the American Meteorological Society highlights recommendations for improving GPS resiliency to space weather.
Almost every aspect of the global economy now depends on GPS. Worldwide, nations are working to create a robust Global Navigation Satellite System (GNSS), which will provide global positioning, navigation, and timing (PNT) services for applications such as aviation, electric power distribution, financial exchange, maritime navigation, and emergency management. The U.S. government is examining the vulnerabilities of GPS, and it is well known that space weather events, such as geomagnetic storms, contribute to errors in single-frequency GPS and are a significant factor for differential GPS. The GPS industry has lately begun to recognize that total electron content (TEC) signal delays, ionospheric scintillation, and solar radio bursts can also interfere with daily operations and that these threats grow with the approach of the next solar maximum, expected to occur in 2013. The key challenges raised by these

circumstances are, first, to better understand the vulnerability of GPS technologies and services to space weather and, second, to develop policies that will build resilience and mitigate risk.

New Policy Statement Released by U.S. Meteorological Organization

Fisher, Genene

Space Weather, Vol. 6, No. 7, S07002, **2008**

http://dx.doi.org/10.1029/2008SW000413

In recognition of the importance of space weather research and services, as well as the need to develop advanced forecasting and mitigation techniques, the American Meteorological Society recently released a policy statement concerning space weather.

Solar radio bursts impact on the International GNSS Service Network during Solar Cycle 24

Manuel **Flores-Soriano***

J. Space Weather Space Clim. **2024**, 14, 32

https://www.swsc-journal.org/articles/swsc/pdf/2024/01/swsc240021.pdf

Solar radio bursts (SRB) are a known source of noise for Global Navigation Satellite Systems (GNSS) such as GPS or Galileo. They can degrade the carrier-to-noise ratio of satellite signals, thereby diminishing system performance and, in severe cases, causing total service outages. Although a small amount of particularly intense events have already been studied in detail, the commonness and intensity of SRBs that could potentially impair GNSS performance remain uncertain. This study broadens the scope beyond merely extreme SRBs, studying the impact of SRBs on GNSS throughout Solar Cycle 24. Solar 1.4 GHz observations from the Radio Solar Telescope Network are used to find the 20 most intense SRBs at that frequency. The impact of each SRB is then evaluated in terms of GNSS signal strength decrease, reduction in the number of available satellites, and precision degradation. The results show that at the GPS L1 frequency only one event presented extended service degradation, while at the L2 frequency, minimum operational requirements were not met by at least one station during seven of the SRBs. Only a modest correlation between performance degradation and SRB intensity is found. In particular, it is reported how some mild SRBs affected satellite signals while others almost ten times more intense went unnoticed. The fundamental role that the SRB circular polarization plays in these discrepancies is shown with new 1.4 GHz circular polarization observations from the SMOS satellite. The different responses of GNSS receivers to SRBs depending on the receiver manufacturer are also explored. **24 September 2011, 11 April 2013, 25 June 2015**

Climate, weather, space weather: model development in an operational context   Review

Doris **Folini**

Journal of Space Weather and Space Climate (JSWSC)   8, A32   **2018**

https://arxiv.org/pdf/1804.11168.pdf

https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc170044.pdf

Aspects of operational modeling for climate, weather, and space weather forecasts are contrasted, with a particular focus on the somewhat conflicting demands of 'operational stability' versus 'dynamic development' of the involved models. Some common key elements are identified, indicating potential for fruitful exchange across communities. Operational model development is compelling, driven by factors that broadly fall into four categories: model skill, basic physics, advances in computer architecture, and new aspects to be covered, from costumer needs over physics to observational data. Evaluation of model skill as part of the operational chain goes beyond an automated skill score. Permanent interaction between 'pure research' and 'operational forecast' people is beneficial to both sides. This includes joint model development projects, although ultimate responsibility for the operational code remains with the forecast provider. The pace of model development reflects operational lead times. The points are illustrated with selected examples, many of which reflect the author's background and personal contacts, notably with the Swiss Weather Service and the Max Planck Institute for Meteorology, Hamburg, Germany. In view of current and future challenges, large collaborations covering a range of expertise are a must - within and across climate, weather, and space weather. To profit from and cope with the rapid progress of computer architectures, supercompute centers must form part of the team.

Polar Cap Patch Prediction in the Expanding Contracting Polar Cap Paradigm

A. Fæhn **Follestad**, L. B. N. Clausen, E. G. Thomas, Y. Jin, A. Coster

Space Weather v. 17, # 11, 1570-1583, **2019**

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019SW002276

Space weather can cause serious disturbances of global navigation satellite systems (GNSS) used for positioning and navigation purposes. This paper describes a new method to forecast space weather disturbances on GNSS at high latitudes, in which we describe the formation and propagation of polar cap patches and predict their arrival at the nightside auroral oval. The space weather prediction model builds on the expanding/contracting polar cap (ECPC) paradigm and total electron content (TEC) observations from the Global Positioning System (GPS) network. The input parameter is satellite observations of the interplanetary magnetic field at the first Lagrange point. To validate our prediction model, we perform a case study in which we compare the results from our prediction model to observations from the GPS TEC data from the MIT's Madrigal database, convection data from Super Dual Auroral radar network, and scintillation data from Svalbard. Our results show that the ECPC paradigm describes the polar cap patch motion well and can be used to predict scintillations of GPS signals at high latitudes.

Solar activity and economic fundamentals: Evidence from 12 geographically disparate power grids

Forbes, Kevin F.; St. Cyr, O. C.
Space Weather, Vol. 6, No. 10, S10003, **2008**
http://dx.doi.org/10.1029/2007SW000350
Using ground-based magnetometer data to estimate geomagnetically induced currents (GICs), scientists studied 12 geographically distinct power grids to see whether GICs and power grid fluctuations were statistically related.

Occurrence rate and duration of space weather impacts on high-frequency radio communication used by aviation

Robyn A. D. **Fiori**1*, Vickal V. Kumar2, David H. Boteler1 and Michael B. Terkildsen2
J. Space Weather Space Clim. **2022**, 12, 21
https://doi.org/10.1051/swsc/2022017
https://www.swsc-journal.org/articles/swsc/pdf/2022/01/swsc220003.pdf
High frequency (HF) radio wave propagation is sensitive to space weather-induced ionospheric disturbances that result from enhanced photoionization and energetic particle precipitation. Recognizing the potential risk to HF radio communication systems used by the aviation industry, as well as potential impacts on GNSS navigation and the risk of elevated radiation levels, the International Civil Aviation Organization (ICAO) initiated the development of a space weather advisory service. For HF systems, this service specifically identifies shortwave fadeout, auroral absorption, polar cap absorption, and post-storm maximum useable frequency depression (PSD) as phenomena impacting HF radio communication and specifies moderate and severe event thresholds to describe event severity. This paper examines the occurrence rate and duration of events crossing the moderate and severe thresholds. Shortwave fadeout was evaluated based on thresholds in the solar X-ray flux. Analysis of 40-years of solar X-ray flux data showed that moderate and severe level solar X-ray flares were observed, on average, 123 and 5 times per 11-year solar cycle, respectively. The mean event duration was 68 min for moderate level events and 132 min for severe level events. Auroral absorption events crossed the moderate threshold for 40 events per solar cycle, with a mean event duration of 5.1 h. The severe threshold was crossed for 3 events per solar cycle with a mean event duration of 12 h. Polar cap absorption had the longest mean duration at ~8 h for moderate events and 1.6 days for severe events; on average, 24 moderate and 13 severe events were observed per solar cycle. Moderate and severe thresholds for shortwave fadeout, auroral absorption, and polar cap absorption were used to determine the expected impacts on HF radio communication. Results for polar cap absorption and shortwave fadeout were consistent with each other, but the expected impact for auroral absorption was shown to be 2–3 times higher. Analysis of 22 years of ionosonde data showed moderate, and severe PSD events occurred, on average, 200 and 56 times per 11-year solar cycle, respectively. The mean event duration was 5.5 h for moderate-level events and 8.5 h for severe-level events. During solar cycles 22 and 23, HF radio communication was expected to experience moderate or severe impacts due to the ionospheric disturbances caused by space weather, a maximum of 163 and 78 days per year, respectively, due to the combined effect of absorption and PSD. The distribution of events is highly non-uniform with respect to the solar cycle: 70% of moderate or severe events were observed during solar maximum compared to solar minimum.

High-Frequency Communications Response to Solar Activity in September 2017 as Observed by Amateur Radio Networks

Nathaniel A. **Frissell**1 , Joshua S. Vega1 , Evan Markowitz1 , Andrew J. Gerrard1 , William D. Engelke2 , Philip J. Erickson3 , Ethan S. Miller4 , R. Carl Luetzelschwab5 , and Jacob Bortnik6
Space Weather 17(1) 118-132 **2019**
sci-hub.tw/10.1029/2018SW002008
Numerous solar flares and coronal mass ejection-induced interplanetary shocks associated with solar active region AR12673 caused disturbances to terrestrial high-frequency (HF, 3–30 MHz) radio communications from 4–14 September 2017. Simultaneously, Hurricanes Irma and Jose caused significant damage to the Caribbean Islands and parts of Florida. The coincidental timing of both the space weather activity and hurricanes was unfortunate, as HF radio was needed for emergency communications. This paper presents the response of HF amateur radio propagation as observed by the Reverse Beacon Network and the Weak Signal Propagation Reporting Network to the space weather events of that period. Distributed data coverage from these dense sources provided a unique mix of global and regional coverage of ionospheric response and recovery that revealed several features of storm time HF propagation dynamics. X-class flares on 6, 7, and 10 September caused acute radio blackouts during the day in the

Caribbean with recovery times of tens of minutes to hours, based on the decay time of the flare. A severe geomagnetic storm with Kpmax = 8+ and SYM-Hmin = −146 nT occurring 7–10 September wiped out ionospheric communications first on 14 MHz and then on 7 MHz starting at ∼1200 UT 8 September. This storm, combined with affects from additional flare and geomagnetic activity, contributed to a significant suppression of effective HF propagation bands both globally and in the Caribbean for a period of 12 to 15 days.
CESRA nugget #2198, May **2019** http://cesra.net/?p=2198

Global response of Magnetic field and Ionosonde observations to intense solar flares on 6 and 10 September 2017

Akiko **Fujimoto**1*, Akimasa Yoshikawa2 and Akihiro Ikeda3
E3S Web of Conferences 62, 01007 (**2018**)
https://www.e3s-conferences.org/articles/e3sconf/pdf/2018/37/e3sconf_strpep2018_01007.pdf
https://doi.org/10.1051/e3sconf/20186201007
Intense X-ray fluxes during solar flares are known to cause enhanced ionization in the Earth's ionospheric D, E and F region. This sudden change of ionospheric electron density profile is serious problem to radio wave communication and navigation system. The ground magnetograms often record the sudden change in the sunlit hemisphere during the enhanced X-ray flux, due to the sudden increase in the global ionospheric current system caused by the flare-induced enhanced ionospheric conductivity. These geomagnetic field disturbances are known as ''solar flare effects'' (SFEs) or geomagnetic crochets [Campbell, 2003]. The typical SFE is increase variation on the equatorial magnetic data. On Ionosonde observation during solar flare event, the High-Frequency (HF) radio wave blackout is often detected in ionogram due to the sudden disturbance in ionosphere. Two intense X-class solar flares occurred on 6 and 10 September 2017. We investigated the magnetic field and Ionosonde responses to the intense solar flare events. Dayside magnetic field variations sudden increased due to the ionospheric disturbance resulting from solar flare. There is no response in night side magnetometer data. The magnitude of SFE (magnetic field) is independent of solar flare x-ray magnitude. We found HF radio wave blackout in ionogram at dayside Ionosonde stations. The duration of blackout is dependent of latitude and local time of Ionosonde stations. There is the different feature of ionogram at night side.

Chapter 21 - How Might the Thermosphere and Ionosphere React to an Extreme Space Weather Event? Review

Tim **Fuller-Rowell***JohnEmmert†MariangelFedrizzi*DanielWeimer‡Mihail V.Codrescu§MarcinPilinski*EricSutton¶RodneyViereck§Joachim (Jimmy)Raeder||EelcoDoornbos#
In: Extreme Events in Geospace Origins, Predictability, and Consequences **2018**, Pages 513-539
http://sci-hub.tw/10.1016/B978-0-12-812700-1.00021-2
This chapter explores how the thermosphere and ionosphere (T-I) might respond to extreme solar events. Three different scenarios are considered: (1) an increase in solar UV and EUV radiation for a number of days, (2) an extreme enhancement in the solar X-rays and EUV radiation associated with a flare, and (3) an extreme CME driving a geomagnetic storm. Estimating the response to the first two scenarios is reasonably well defined, and although they would certainly impact the T-I system, those impacts could potentially be mitigated. In contrast, the response to an extreme geomagnetic storm is significantly more complicated, making the response much more uncertain, and mitigation more challenging. The question is, if an 1859 Carrington-level CME hit Earth, how might the thermosphere and ionosphere respond? Firstly, the response would be dependent upon how the magnetosphere reacts and channels the energy into the upper atmosphere. The assumption is the magnetospheric convection and auroral precipitation inputs would look similar to the 2003 Halloween or 2000 Bastille Day storms, but stronger and more expanded towards middle latitudes. For a Halloween or Bastille-level geomagnetic storm, the sequence of physical processes in the thermosphere and ionosphere are mostly understood, and the physics-based models have been tuned for this level of event. For an extreme solar storm, it is unclear what the magnitude of the driving forces would be, and if the T-I response would be a natural linear extrapolation or if nonlinear processes would begin to dominate. A numerical simulation has been performed with a coupled thermosphere ionosphere model to quantify the likely response to an extreme geomagnetic storm. The simulation predicts the neutral atmosphere would experience horizontal winds of 1500 m s−1, vertical winds exceeding 150 m s−1, and large increases in neutral density with the "top" of the thermosphere (where collisions no longer dominate) rising to well above 1000 km. The expansion of the atmosphere during an extreme event and the increase in neutral density has the direct effect of enhancing drag on a spacecraft, changing its orbit, and raising the uncertainty of its position. With the proliferation of space debris, the challenge of collision avoidance is of mounting concern, which further raises the importance of

accurate orbit prediction. Predicting the ionosphere response is more challenging because there is significant uncertainty in quantifying some of the other driver-response relationships, such as the magnitude and shielding time-scale of the penetration electric field, and the possible feedback to the magnetosphere. Total electron content at mid latitude could exceed 1000 TEC units, which together with steep gradients and more structure will severely impact critical communications and satellite navigation accuracy.

Space Weather Forecasting at IZMIRAN

S. P. **Gaidash**, A. V. Belov, M. A. Abunina, A. A. Abunin
Geomagnetism and Aeronomy December **2017**, Volume 57, Issue 7, pp 869–876

http://sci-hub.tw/10.1134/S0016793217070088
Since 1998, the Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation (IZMIRAN) has had an operating heliogeophysical service—the Center for Space Weather Forecasts. This center transfers the results of basic research in solar–terrestrial physics into daily forecasting of various space weather parameters for various lead times. The forecasts are promptly available to interested consumers. This article describes the center and the main types of forecasts it provides: solar and geomagnetic activity, magnetospheric electron fluxes, and probabilities of proton increases. The challenges associated with the forecasting of effects of coronal mass ejections and coronal holes are discussed. Verification data are provided for the center's forecasts.

The growth of the commercial sector in space science

JL **Gannon**, N Lugaz
Space Weather e2021SW002817 **2021**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021SW002817
https://doi.org/10.1029/2021SW002817
As space science in the commercial sector grows, new opportunities emerge for data availability and collaboration between the public and private sectors.

Space Weather Effects Produced by the Ring Current Particles **Review**

Natalia **Ganushkina**, Allison Jaynes, Michael Liemohn
Space Science Reviews Volume 212, Issue 3–4, pp 1315–1344 **2017**
https://link.springer.com/content/pdf/10.1007%2Fs11214-017-0412-2.pdf
One of the definitions of space weather describes it as the time-varying space environment that may be hazardous to technological systems in space and/or on the ground and/or endanger human health or life. The ring current has its contributions to space weather effects, both in terms of particles, ions and electrons, which constitute it, and magnetic and electric fields produced and modified by it at the ground and in space. We address the main aspects of the space weather effects from the ring current starting with brief review of ring current discovery and physical processes and the Dst-index and predictions of the ring current and storm occurrence based on it. Special attention is paid to the effects on satellites produced by the ring current electrons. The ring current is responsible for several processes in the other inner magnetosphere populations, such as the plasmasphere and radiation belts which is also described. Finally, we discuss the ring current influence on the ionosphere and the generation of geomagnetically induced currents (GIC).

Forecasting methods for occurrence and magnitude of proton storms with solar soft X rays

H. A. **Garcia**
Space Weather 2, S02002. **2004** (doi:10.1029/2003SW000001)
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2003SW000001
sci-hub.se/10.1029/2003sw000001
Solar energetic proton (SEP) events in the vicinity of Earth have the potential of affecting the performance of civilian, military, and research satellites, including such diverse functions as communications, spacecraft operations, surveillance, navigation, and life support systems. The National Oceanic and Atmospheric Administration's (NOAA) Space Environment Center and the U. S. Air Force Weather Agency cooperate to provide advance warnings of SEP events. Their explicit duties include the need to continually upgrade and improve the accuracy, timeliness, and scope of SEP forecasts. Previous work on this topic established the empirical connection between SEPs and low-temperature X-ray flares. The main focus of the present work is to improve the quality of SEP forecasts by enhancing the size and content of the flare database used to quantify the probability model, tuning the model with imposed operational constraints, and augmenting each SEP prediction with an estimate of the magnitude of the particle event itself.

Prediction and warning system of SEP events and solar flares for risk estimation in space launch operations

Alberto **García-Rigo**1*, Marlon Núñez2, Rami Qahwaji3, Omar Ashamari3, Piers Jiggens4, Gustau Pérez1, Manuel Hernández-Pajares1 and Alain Hilgers
J. Space Weather Space Clim., 6, A28 (**2016**)
http://www.swsc-journal.org/articles/swsc/pdf/2016/01/swsc150014.pdf
A web-based prototype system for predicting solar energetic particle (SEP) events and solar flares for use by space launch operators is presented. The system has been developed as a result of the European Space Agency (ESA) project SEPsFLAREs (Solar Events Prediction system For space LAunch Risk Estimation). The system consists of several modules covering the prediction of solar flares and early SEP Warnings (labeled Warning tool), the prediction of SEP event occurrence and onset, and the prediction of SEP event peak and duration. In addition, the system acquires data for solar flare nowcasting from Global Navigation Satellite Systems (GNSS)-based techniques (GNSS Solar Flare Detector, GSFLAD and the Sunlit Ionosphere Sudden Total Electron Content Enhancement Detector, SISTED) as additional independent products that may also prove useful for space launch operators. **5-8 Dec 2006, 18th April, 2014**

Space Weather Effects of Solar Radio Bursts

Dale **Gary**∗1 and Gelu Nita
CESRA Abstract **2016**
http://cesra2016.sciencesconf.org/conference/cesra2016/pages/CESRA2016_prog_abs_book_v1.pdf
The effects of solar radio noise on wireless navigation and communications systems have been clearly demonstrated in a few cases, with the most serious being outages of the Global Positioning System (GPS) over the entire sunlit hemisphere of the Earth in December 2006. We review what is known about both the actual observed effects and assessments of the prevalence of such effects in the future, and point out the need for better monitoring of solar bursts. We also discuss strategies for reducing or mitigating the threat of solar radio noise on wireless technological systems.

Why Space Weather Is Relevant to Electrical Power Systems

C. T. **Gaunt**
Space Weather Volume 14, Issue 1 January **2016** Pages 2–9

Reducing uncertainty – responses for electricity utilities to severe solar storms

Charles Trevor **Gaunt**
J. Space Weather Space Clim. 4 (**2014**) A01
http://www.swsc-journal.org/articles/swsc/pdf/2014/01/swsc130019.pdf
Until recently, electricity utilities in mid- and low-latitude regions believed that solar storms had no (or only insignificant) effect on their power systems. Then it was noticed that the onset of damage in several large transformers, leading to their failure, correlated very closely with the Halloween storm of 2003. Since then engineers have started to appreciate that a very severe storm could have serious consequences outside the high-latitude regions. There are many uncertainties in predicting the effects of solar storms on electrical systems. The severity and time of arrival of a storm are difficult to model; so are the geomagnetically induced currents (GICs) expected to flow in the power networks. Published information about the responses of different types of transformers to GICs is contradictory. Measurements of the abnormal power flows in networks during solar storms generally do not take into account the effects of the current distortion and unbalance, potentially giving misleading signals to the operators. The normal requirement for optimum system management, while allowing for the possibility of faults caused by lightning, birds and other causes, limits the capacity of system operators to respond to the threats of GICs, which are not assessed easily by the $N - 1$ reliability criterion. A utility's response to the threat of damage by GICs depends on the expected frequency and magnitude of solar storms. Approaches to formulating a response are located in a system model incorporating space physics, network analysis, transformer engineering, network reliability and decision support and the benefits are identified. Approaches adopted in high-latitude regions might not be appropriate where fewer storms are expected to reach damaging levels. The risks of an extreme storm cannot be ignored, and understanding the response mechanisms suitable for low-latitude regions has the capacity to inform and reduce the uncertainty for power systems planners and operators worldwide.

Developing a nowcasting capability for X-Class solar flares using VLF radiowave propagation changes

Harriet E. **George**, Craig J. Rodger, Mark A. Clilverd, Kathy Cresswell-Moorcock, James B. Brundell, Neil R. Thomson
Space Weather **2019**

https://doi.org/10.1029/2019SW002297
https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2019SW002297
A technique for analysing very low frequency (VLF) radiowave signals is investigated in order to achieve rapid, real-time detection of large solar flares, through the monitoring of changes in VLF radio signal propagation conditions. The reliability of the use of VLF phase and amplitude perturbations to determine the X-ray fluxes involved during 10 large solar flare events (>X1) is examined. Linear regression analysis of signals from the NPM transmitter in Hawaii, received at Arrival Heights, Scott Base, Antarctica over the years 2011-2015 shows that VLF phase perturbations during large solar flares have a 1.5-3 times lower mean square error when modelling the long wavelength X-ray fluxes than the equivalent short wavelength fluxes. The use of VLF amplitude observations to determine long or short wavelength X-ray flux levels have a 4-10 times higher mean square error than when using VLF phase. Normalised linear regression analysis identifies VLF phase as the most important parameter in the regression, followed by solar zenith angle at the mid-point of the propagation path, then the initial solar X-ray flux level (from 5 min before the impact of the solar flare), with F10.7 cm flux from the day beforehand providing the least important contribution. Transmitter phase measurements are more difficult to undertake than amplitude. However, networks of VLF receivers already exist which include the high quality phase capability required for such a nowcasting product. Such narrowband VLF data can be a redundant source of flare monitoring if satellite data is not available.

The Flare Likelihood and Region Eruption Forecasting (FLARECAST) Project: Flare forecasting in the big data & machine learning era **Review**

M. K. **Georgoulis**, D. S. Bloomfield, M. Piana, A. M. Massone, M. Soldati, P. T. Gallagher, E. Pariat, N. Vilmer, E. Buchlin, F. Baudin, A. Csillaghy, H. Sathiapal, D. R. Jackson, P. Alingery, F. Benvenuto, C. Campi, K. Florios, C. Gontikakis, C. Guennou, J. A. Guerra, I. Kontogiannis, V. Latorre, S. A. Murray, S.-H. Park, S. von Stachelski, A. Torbica, D. Vischi, M. Worsfold
Journal of Space Weather and Space Climate, **2021**
https://arxiv.org/pdf/2105.05993.pdf
The EU funded the FLARECAST project, that ran from Jan 2015 until Feb 2018. FLARECAST had a R2O focus, and introduced several innovations into the discipline of solar flare forecasting. FLARECAST innovations were: first, the treatment of hundreds of physical properties viewed as promising flare predictors on equal footing, extending multiple previous works; second, the use of fourteen (14) different ML techniques, also on equal footing, to optimize the immense Big Data parameter space created by these many predictors; third, the establishment of a robust, three-pronged communication effort oriented toward policy makers, space-weather stakeholders and the wider public. FLARECAST pledged to make all its data, codes and infrastructure openly available worldwide. The combined use of 170+ properties (a total of 209 predictors are now available) in multiple ML algorithms, some of which were designed exclusively for the project, gave rise to changing sets of best-performing predictors for the forecasting of different flaring levels. At the same time, FLARECAST reaffirmed the importance of rigorous training and testing practices to avoid overly optimistic pre-operational prediction performance. In addition, the project has (a) tested new and revisited physically intuitive flare predictors and (b) provided meaningful clues toward the transition from flares to eruptive flares, namely, events associated with coronal mass ejections (CMEs). These leads, along with the FLARECAST data, algorithms and infrastructure, could help facilitate integrated space-weather forecasting efforts that take steps to avoid effort duplication. In spite of being one of the most intensive and systematic flare forecasting efforts to-date, FLARECAST has not managed to convincingly lift the barrier of stochasticity in solar flare occurrence and forecasting: solar flare prediction thus remains inherently probabilistic. **12 Nov 2012, 2 January 2015, 5 Sep 2017**

Solar Radio Burst Statistics and Implications for Space Weather Effects

O. D. **Giersch**, J. Kennewell, M. Lynch
Space Weather 16 November **2017** Vol: 15, Pages: 1511–1522
http://sci-hub.tw/10.1002/2017SW001658
Solar radio bursts have the potential to affect space and terrestrial navigation, communication, and other technical systems that are sometimes overlooked. However, over the last decade a series of extreme L band solar radio bursts in December 2006 have renewed interest in these effects. In this paper we point out significant deficiencies in the solar radio data archives of the National Centers for Environmental Information (NCEI) that are used by most researchers in analyzing and producing statistics on solar radio burst phenomena. In particular, we examine the records submitted by the United States Air Force (USAF) Radio Solar Telescope Network (RSTN) and its predecessors from the period 1966 to 2010. Besides identifying substantial missing burst records we show that different observatories can have statistically different burst distributions, particularly at 245 MHz. We also point out that different solar cycles may show statistically different distributions and that it is a mistake to assume that the Sun shows similar behavior in different sunspot cycles. Large solar radio bursts are not confined to the period around sunspot maximum, and prediction of such events that utilize historical data will invariably be an underestimate due

to archive data deficiencies. It is important that researchers and forecasters use historical occurrence frequency with caution in attempting to predict future cycles.
2 The Solar Radio Burst Contribution to Space Weather

Solar Rotation Multiples in Space-Weather Effects

Agnieszka **Gil**, Renata Modzelewska, Anna Wawrzaszek, Bozena Piekart & Tadeusz Milosz
Solar Physics volume 296, Article number: 128 (**2021**)
https://link.springer.com/content/pdf/10.1007/s11207-021-01873-7.pdf
https://doi.org/10.1007/s11207-021-01873-7
The solar rotation period is the most prominent mid-term periodicity in the temporal behaviour of solar, heliospheric, and geomagnetic parameters. It is also a cause of the repeatedly appearing geomagnetic storms originating from the corotating interaction regions (CIRs). Since geomagnetic CIR-driven storms have a natural periodic character, and geomagnetic storms impact energy infrastructure via geomagnetically induced currents, it is of interest whether this periodic character is also noticeable in the temporal behaviour of **electrical-grid failures** (EGFs), which, at least to some extent, might be of solar origin.

Evaluating the relationship between strong geomagnetic storms and electric grid failures in Poland using the geoelectric field as a GIC proxy

Agnieszka **Gil**, Monika Berendt-Marchel, Renata Modzelewska, Szczepan Moskwa, Agnieszka Siluszyk, Marek Siluszyk, Lukasz Tomasik, Anna Wawrzaszek and Anna Wawrzynczak
J. Space Weather Space Clim. **2021**, 11, 30
https://doi.org/10.1051/swsc/2021013
https://www.swsc-journal.org/articles/swsc/pdf/2021/01/swsc200092.pdf
We study intense geomagnetic storms (Dst < −100nT) during the first half of the solar cycle 24. This type of storm appeared only a few times, mostly associated with southwardly directed heliospheric magnetic field Bz. Using various methods such as self-organizing maps, statistical and superposed epoch analysis, we show that during and right after intense geomagnetic storms, there is growth in the number of transmission line failures. We also examine the temporal changes in the number of failures during 2010-2014 and find that the growing linear tendency of electrical grid failure occurrence is possibly connected with solar activity. We compare these results with the geoelectric field calculated for the region of Poland using a 1-D layered conductivity Earth model.

Inner Radiation Belt Simulations During the Successive Geomagnetic Storm Event of February 2022

Kirolosse M. **Girgis**, Tohru Hada, Akimasa Yoshikawa, Shuichi Matsukiyo, Abraham C.-L. Chian, Ezequiel Echer
Space Weather Volume22, Issue7 July **2024** e2023SW003789
https://doi.org/10.1029/2023SW003789
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2023SW003789
Starting from **29 January 2022**, a series of solar eruptions triggered a moderate geomagnetic storm on **3 February 2022**, followed subsequently by another. Despite the typically minimal impact of unintense storms on space technology, 38 out of the 49 Starlink satellites underwent orbital decay, re-entering Earth's atmosphere. These satellite losses were attributed to enhanced atmospheric drag conditions. This study employs numerical simulations, utilizing our test particle simulation code, to investigate the dynamics of the inner radiation belt during the two magnetic storms. Our analysis reveals an increase in proton density and fluxes during the transition from the recovery phase of the first storm to the initial phase of the second, primarily driven by intense solar wind dynamic pressure. Additionally, we assess Single Event Upset (SEU) rates, which exhibit a 50% increase in comparison to initial quiet conditions.

Evaluation of SaRIF high-energy electron reconstructions and forecasts

S. A. **Glauert**, R. B. Horne, P. Kirsch,
Space Weather e2021SW002822 **2021**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021SW002822
https://doi.org/10.1029/2021SW002822
Increasing numbers of satellites are orbiting through the Earth's radiation belts, and the range of orbits being commonly used is also growing. As a result, there is an increasing need for services to help protect satellites from space weather. The Satellite RIsk prediction and radiation Forecast (SaRIF) system provides reconstructions and forecasts of the high-energy electron flux throughout the outer radiation belt and translates these predictions into

charging currents, dose rates, total ionising dose and risk indicators. SaRIF both informs satellite operators of current and expected conditions and provides a tool to aid in post-event analysis. The reconstructions and forecasts are provided by the British Antarctic Survey Radiation Belt Model (BAS-RBM) running as part of an automatic system using real-time data to specify the boundary conditions and drive processes within the physics-based model. If SaRIF is to provide a useful tool, then the accuracy of the reconstructions and forecasts needs to be understood. Here we assess the accuracy of the simulations for geostationary orbit by comparing the model output with measurements made by the GOES 14 spacecraft for the period March - September 2019. No GOES 14 data was used to create the reconstruction or forecasts. We show that, with some improvements to the original system, the reconstructions have a prediction efficiency of 0.82 for >800 keV electrons and 0.87 for >2 MeV electrons, with corresponding prediction efficiencies of 0.59 and 0.78 for the forecasts.

A 30-Year Simulation of the Outer Electron Radiation Belt

S. A. **Glauert** R. B. Horne N. P. Meredith

Space Weather Volume16, Issue10 October **2018** Pages 1498-1522
https://doi.org/10.1029/2018SW001981

As society becomes more reliant on satellite technology, it is becoming increasingly important to understand the radiation environment throughout the Van Allen radiation belts. Historically most satellites have operated in low Earth orbit or geostationary orbit (GEO), but there are now over 100 satellites in medium Earth orbit (MEO). Additionally, satellites using electric orbit raising to reach GEO may spend hundreds of days on orbits that pass through the heart of the radiation belts. There is little long-term data on the high-energy electron flux, responsible for internal charging in satellites, available for MEO. Here we simulate the electron flux between the outer edge of the inner belt and GEO for 30 years. We present a method that converts the >2-MeV flux measured at GEO by the Geostationary Operational Environmental Satellites spacecraft into a differential flux spectrum to provide an outer boundary condition. The resulting simulation is validated using independent measurements made by the Galileo In-Orbit Validation Element-B spacecraft; correlation coefficients are in the range 0.72 to 0.88, and skill scores are between 0.6 and 0.8 for a range of $L*$ and energies. The results show a clear solar cycle variation and filling of the slot region during active conditions and that the worst case spectrum overlaps that derived independently for the limiting extreme event. The simulation provides a resource that can be used by satellite designers to understand the MEO environment, by space insurers to help resolve the cause of anomalies and by satellite operators to plan for the environmental extremes.

Community-wide validation of geospace model local K-index predictions to support model transition to operations

A. **Glocer**, L. Rastätter, M. Kuznetsova, A. Pulkkinen, H. J. Singer, C. Balch, D. Weimer, D. Welling, M. Wiltberger, J. Raeder, R. S. Weigel, J. McCollough, S. Wing

Space Weather Volume 14, Issue 7 July **2016** Pages 469–480

We present the latest result of a community-wide space weather model validation effort coordinated among the Community Coordinated Modeling Center (CCMC), NOAA Space Weather Prediction Center (SWPC), model developers, and the broader science community. Validation of geospace models is a critical activity for both building confidence in the science results produced by the models and in assessing the suitability of the models for transition to operations. Indeed, a primary motivation of this work is supporting NOAA/SWPC's effort to select a model or models to be transitioned into operations. Our validation efforts focus on the ability of the models to reproduce a regional index of geomagnetic disturbance, the local K-index. Our analysis includes six events representing a range of geomagnetic activity conditions and six geomagnetic observatories representing midlatitude and high-latitude locations. Contingency tables, skill scores, and distribution metrics are used for the quantitative analysis of model performance. We consider model performance on an event-by-event basis, aggregated over events, at specific station locations, and separated into high-latitude and midlatitude domains. A summary of results is presented in this report, and an online tool for detailed analysis is available at the CCMC.

EUV imaging and spectroscopy for improved space weather forecasting **Review**

Leon **Golub**1*, Peter Cheimets1, Edward E. DeLuca1, Chad A. Madsen1, Katharine K. Reeves1, Jenna Samra1, Sabrina Savage2, Amy Winebarger2 and Alexander R. Bruccoleri3

J. Space Weather Space Clim. **2020**, 10, 37
https://doi.org/10.1051/swsc/2020040
https://www.swsc-journal.org/articles/swsc/pdf/2020/01/swsc200031.pdf

Accurate predictions of harmful space weather effects are mandatory for the protection of astronauts and other assets in space, whether in Earth or lunar orbit, in transit between solar system objects, or on the surface of other planetary bodies. Because the corona is multithermal (i.e., structured not only in space but also in temperature), wavelength-separated data provide crucial information that is not available to imaging methods that integrate over temperature.

The extreme ultraviolet (EUV) wavelengths enable us to focus directly on high temperature coronal plasma associated with solar flares, coronal mass ejections (CMEs), and shocked material without being overwhelmed by intensity from the solar disk. Both wide-field imaging and spectroscopic observations of the solar corona taken from a variety of orbits (e.g., Earth, L1, or L5) using suitably-chosen EUV instrumentation offer the possibility of addressing two major goals to enhance our space weather prediction capability, namely: (1) Improve our understanding of the coronal conditions that control the opening and closing of the corona to the heliosphere and consequent solar wind streams, and (2) Improve our understanding of the physical processes that control the early evolution of CMEs and the formation of shocks, from the solar surface out into the extended corona. **11 Feb 2010, 3 Nov 2010, 12 March 2012, 12 December 2012**

What Sustained Multi-Disciplinary Research Can Achieve: The Space Weather Modeling Framework

Gombosi, Tamas I.; Chen, Yuxi; Glocer, Alex; Huang, Zhenguang; et al.
Journal of Space Weather and Space Climate **11**, 42 **2021**, 55 pages
https://arxiv.org/pdf/2105.13227.pdf
https://www.swsc-journal.org/articles/swsc/pdf/forth/swsc210015.pdf
https://doi.org/10.1051/swsc/2021020
MHD-based global space weather models have mostly been developed and maintained at academic institutions. While the "free spirit" approach of academia enables the rapid emergence and testing of new ideas and methods, the lack of long-term stability and support makes this arrangement very challenging. This paper describes a successful example of a university-based group, the Center of Space Environment Modeling (CSEM) at the University of Michigan, that developed and maintained the Space Weather Modeling Framework (SWMF) and its core element, the BATS-R-US extended MHD code. It took a quarter of a century to develop this capability and reach its present level of maturity that makes it suitable for research use by the space physics community through the Community Coordinated Modeling Center (CCMC) as well as operational use by the NOAA Space Weather Prediction Center (SWPC).

Anthropogenic Space Weather

T. I. **Gombosi**, D. N. Baker, A. Balogh, P. J. Erickson, J. D. Huba…
Space Science Reviews Volume 212, Issue 3–4, pp 985–1039 **2017**
Part of the following topical collections: The Scientific Foundation of Space Weather
http://link.springer.com/content/pdf/10.1007%2Fs11214-017-0357-5.pdf
http://sci-hub.cc/10.1007/s11214-017-0357-5
Anthropogenic effects on the space environment started in the late 19th century and reached their peak in the 1960s when high-altitude nuclear explosions were carried out by the USA and the Soviet Union. These explosions created artificial radiation belts near Earth that resulted in major damages to several satellites. Another, unexpected impact of the high-altitude nuclear tests was the electromagnetic pulse (EMP) that can have devastating effects over a large geographic area (as large as the continental United States). Other anthropogenic impacts on the space environment include chemical release experiments, high-frequency wave heating of the ionosphere and the interaction of VLF waves with the radiation belts. This paper reviews the fundamental physical process behind these phenomena and discusses the observations of their impacts.

Mexican SpaceWeather Service (SCiESMEX)

J. A. **Gonzalez-Esparza**, V. De la Luz, P. CoronaRomero, J. C. Mejia-Ambriz, L. X. Gonzalez, M. A. Sergeeva, E. Romero-Hernandez, and E. AguilarRodriguez
Space Weather Quarterly v. 14 No. 1 p. 6-14 **2017**
http://onlinelibrary.wiley.com/doi/10.1002/swq.13/pdf
Legislative modifications of the General Civil Protection Law in Mexico in 2014 included specific references to space hazards and space weather phenomena. The legislation is consistent with United Nations promotion of international engagement and cooperation on space weather awareness, studies, and monitoring. These internal and external conditions motivated the creation of a space weather service in Mexico. The Mexican Space Weather Service (SCiESMEX in Spanish) (www.sciesmex.unam. mx) was initiated in October 2014 and is operated by the Institute of Geophysics at the Universidad Nacional Autonoma de Mexico (UNAM). SCiESMEX became a Regional Warning Center of the International Space Environment Services (ISES) in June 2015. We present the characteristics of the service, some products, and the initial actions for developing a space weather strategy in Mexico. The service operates a computing infrastructure including a web application, data repository, and a high-performance computing server to run numerical models. SCiESMEX uses data of the ground-based instrumental network of the National Space Weather Laboratory (LANCE), covering solar radio burst emissions, solar wind and interplanetary disturbances (by interplanetary scintillation observations), geomagnetic measurements, and analysis

of the total electron content (TEC) of the ionosphere (by employing data from local networks of GPS receiver stations).

The multiview observatory for solar terrestrial science (MOST)

N. **Gopalswamy**1* , S. Christe1 , S. F. Fung1 , Q. Gong1 , J. R. Gruesbeck1 , +++

Journal of Atmospheric and Solar-Terrestrial Physics, Volume 254, article id. 106165. **2024**

https://arxiv.org/pdf/2303.02895

https://ntrs.nasa.gov/api/citations/20220013621/downloads/GopalswamyNat_MOST_WP.pdf

We report on a study of the Multiview Observatory for Solar Terrestrial Science (MOST) mission that will provide comprehensive imagery and time series data needed to understand the magnetic connection between the solar interior and the solar atmosphere/inner heliosphere. MOST will build upon the successes of SOHO and STEREO missions with new views of the Sun and enhanced instrument capabilities. This article is based on a study conducted at NASA Goddard Space Flight Center that determined the required instrument refinement, spacecraft accommodation, launch configuration, and flight dynamics for mission success. MOST is envisioned as the next generation great observatory positioned to obtain three-dimensional information of large-scale heliospheric structures such as coronal mass ejections, stream interaction regions, and the solar wind itself. The MOST mission consists of 2 pairs of spacecraft located in the vicinity of Sun-Earth Lagrange points L4 (MOST1, MOST3) and L5 (MOST2 and MOST4). The spacecraft stationed at L4 (MOST1) and L5 (MOST2) will each carry seven remote-sensing and three in-situ instrument suites, including a novel radio package known as the Faraday Effect Tracker of Coronal and Heliospheric structures (FETCH). MOST3 and MOST4 will carry only the FETCH instruments and are positioned at variable locations along the Earth orbit up to 20° ahead of L4 and 20° behind L5, respectively. FETCH will have polarized radio transmitters and receivers on all four spacecraft to measure the magnetic content of solar wind structures propagating from the Sun to Earth using the Faraday rotation technique. The MOST mission will be able to sample the magnetized plasma throughout the Sun-Earth connected space during the mission lifetime over a solar cycle.

The Sun and Space Weather **Review**

Nat **Gopalswamy**

Atmosphere, vol. 13, issue 11, p. 1781, **2022** **File**

https://www.mdpi.com/2073-4433/13/11/1781/pdf?version=1666956880

https://doi.org/10.3390/atmos13111781

https://arxiv.org/ftp/arxiv/papers/2211/2211.06775.pdf

https://www.mdpi.com/2073-4433/13/11/1781

The explosion of space weather research since the early 1990s has been partly fueled by the unprecedented, uniform, and extended observations of solar disturbances from space- and ground-based instruments. Coronal mass ejections (CMEs) from closed magnetic field regions and high-speed streams (HSS) from open-field regions on the Sun account for most of the disturbances relevant to space weather. The main consequences of CMEs and HSS are their ability to cause geomagnetic storms and accelerate particles. Particles accelerated by CME-driven shocks can pose danger to humans and their technological structures in space. Geomagnetic storms produced by CMEs and HSS-related stream interaction regions also result in particle energization inside the magnetosphere that can have severe impact on satellites operating in the magnetosphere. Solar flares are another aspect of solar magnetic energy release, mostly characterized by the sudden enhancement in electromagnetic emission at various wavelengths—from radio waves to gamma-rays. Flares are responsible for the sudden ionospheric disturbances and prompt perturbation of Earth's magnetic field known as magnetic crochet. Nonthermal electrons accelerated during flares can emit intense microwave radiation that can drown spacecraft and radar signals. This review article summarizes major milestones in understanding the connection between solar variability and space weather**. 1997 October 6, 1998 June 11, 2002 April 21, 29 Oct-1 Nov 2003, 15 Jan 2005, 2005 May 13, 14 Dec 2006, 9 Mar 2011, 2011 August 4, 30 May-1 Jun 2013,**

Solar Activity and Space Weather **Review**

Nat **Gopalswamy**, Pertti Mäkelä, Seiji Yashiro, Sachiko Akiyama, Hong Xie

Journal of Physics: Conference Series, Proc. 2nd International Symposium on Space Science 2021, LAPAN, Indonesia **2022**

https://arxiv.org/ftp/arxiv/papers/2201/2201.02724.pdf **File**

After providing an overview of solar activity as measured by the sunspot number (SSN) and space weather events during solar cycles (SCs) 21-24, we focus on the weak solar activity in SC 24. The weak solar activity reduces the number of energetic eruptions from the Sun and hence the number of space weather events. The speeds of coronal mass ejections (CMEs), interplanetary (IP) shocks, and the background solar wind all declined in SC 24. One of the main heliospheric consequences of weak solar activity is the reduced total (magnetic + gas) pressure, magnetic field strength, and Alfvén speed. There are three groups of phenomena that decline to different degrees in SC 24 relative to the corresponding ones in SC 23: (i) those that decline more than SSN does, (ii) those that decline like SSN, and

(iii) those that decline less than SSN does. The decrease in the number of severe space weather events such as high-energy solar energetic particle (SEP) events and intense geomagnetic storms is deeper than the decline in SSN. CMEs expand anomalously and hence their magnetic content is diluted resulting in weaker geomagnetic storms. The reduction in the number of intense geomagnetic storms caused by corotating interaction regions is also drastic. The diminished heliospheric magnetic field in SC 24 reduces the efficiency of particle acceleration, resulting in fewer high-energy SEP events. The numbers of IP type II radio bursts, IP socks, and high-intensity energetic storm particle events closely follow the number of fast and wide CMEs (and approximately SSN). The number of halo CMEs in SC 24 declines less than SSN does, mainly due to the weak heliospheric state. Phenomena such as IP CMEs and magnetic clouds related to frontside halos also do not decline significantly. The mild space weather is likely to continue in SC 25, whose strength has been predicted to be not too different from that of SC 24.
Table 1. Comparison of various parameters between solar cycles 23 and 24
Table 2. List of intense storms in cycle 23 and 24 and the associated coronal hole properties

Predictability of the Variable Solar Terrestrial Coupling (PRESTO): The New Scientific Program of SCOSTEP

Nat **Gopalswamy**
VarSITI Newsletter Vol. 21 p. 15-16 **2019**
http://newserver.stil.bas.bg/varsiti/newsL/VarSITI_Newsletter_Vol21.pdf

Properties of DH Type II Radio Bursts and Their Space Weather Implications

N. **Gopalswamy**, P. Mäkelä
submitted to the URSI AP-RASC 2019 **2018**
https://arxiv.org/ftp/arxiv/papers/1810/1810.11173.pdf
We report on the properties of type II radio bursts observed by the Radio and Plasma Wave Experiment (WAVES) on board the Wind spacecraft over the past two solar cycles. We confirm that the associated coronal mass ejections (CMEs) are fast and wide, more than half the CMEs being halos. About half of the type II bursts extend down to 0.5 MHz, corresponding to a heliocentric distance of tens of solar radii. The DH type II bursts are mostly confined to the active region belt and their occurrence rate follows the solar activity cycle. Type II burst occurring on the western hemisphere of the Sun and extending to lower frequencies are good indicators of a solar energetic particle event.
2001/12/28 , 2002/07/20 , 2005/07/27, 2005 September 7, 2011 September 22, 2013/06/21 , 2014 February 25
Table 1. Large SEP events from the east limb

Extreme Solar Eruptions and their Space Weather Consequences **Review**

Nat **Gopalswamy**
In: Extreme Events in Geospace
Origins, Predictability, and Consequences **Book**
Editor: Natalia **Buzulukova**, Elsevier, **2018**, 798 p. **File**
p. 37-63 sci-hub.se/10.1016/B978-0-12-812700-1.00002-9
https://sci-hub.tw/10.1016/B978-0-12-812700-1.00002-9
Solar eruptions generally refer to coronal mass ejections (CMEs) and flares. Both are important sources of space weather. Solar flares cause sudden change in the ionization level in the ionosphere. CMEs cause solar energetic particle (SEP) events and geomagnetic storms. A flare with unusually high intensity and/or a CME with extremely high energy can be thought of examples of extreme events on the Sun. These events can also lead to extreme SEP events and/or geomagnetic storms. Ultimately, the energy that powers CMEs and flares are stored in magnetic regions on the Sun, known as active regions. Active regions with extraordinary size and magnetic field have the potential to produce extreme events. Based on current data sets, we estimate the sizes of one-in-hundred and one-in-thousand year events as an indicator of the extremeness of the events. We consider both the extremeness in the source of eruptions and in the consequences. We then compare the estimated 100-year and 1000-year sizes with the sizes of historical extreme events measured or inferred.
Carrington flare , 2003 October 28, 2004 November 10, October 2014
Table 1. Integral fluence values for different models in units of 1010 p cm-2
Table 2. Expected 100-year and 1000-year event sizes estimated from the tail of observed distributions fitted to various functions.

History and Development of Coronal Mass Ejections as a Key Player in Solar Terrestrial Relationship **Review**

N. **Gopalswamy**
Geoscience Letters Volume 3, article id.8, 18 pp. **2016** **File**
http://arxiv.org/pdf/1602.03665v1.pdf

Coronal mass ejections (CMEs) are relatively a recently-discovered phenomenon, in 1971, some fifteen years into the Space Era. It took another two decades to realize that CMEs are the most important players in solar terrestrial relationship as the root cause of severe weather in Earth's space environment. CMEs are now counted among the major natural hazards because they cause large solar energetic particle (SEP) events and major geomagnetic storms, both of which pose danger to humans and their technology in space and ground. Geomagnetic storms discovered in the 1700s, solar flares discovered in the 1800s, and SEP events discovered in the1900s are all now found to be closely related to CMEs via various physical processes occurring at various locations in and around CMEs, when they interact with the ambient medium. This article identifies a number of key developments that preceded the discovery of white-light CMEs suggesting that CMEs were waiting to be discovered. The last two decades witnessed an explosion of CME research following the launch of the Solar and Heliospheric Observatory mission in 1995, resulting in the establishment of a full picture of CMEs.

Low-Frequency Radio Bursts and Space Weather **Review**

Nat **Gopalswamy**

URSI Asia-Pacific Radio Science Conference in Seoul, August 21-25, 2016 **2016**

http://arxiv.org/pdf/1605.02218v1.pdf **File**

Low-frequency radio phenomena are due to the presence of nonthermal electrons in the interplanetary (IP) medium. Understanding these phenomena is important in characterizing the space environment near Earth and other destinations in the solar system. Substantial progress has been made in the past two decades, because of the continuous and uniform data sets available from space-based radio and white-light instrumentation. This paper highlights some recent results obtained on IP radio phenomena. In particular, the source of type IV radio bursts, the behavior of type III storms, shock propagation in the IP medium, and the solar-cycle variation of type II radio bursts are considered. All these phenomena are closely related to solar eruptions and active region evolution. The results presented were obtained by combining data from the Wind and SOHO missions.

CMEs during the Two Activity Peaks in Cycle 24 and their Space Weather Consequences

N. **Gopalswamy**, P. Mäkelä, S. Akiyama, S. Yashiro, N. Thakur

Sun and Geosphere, **2015**

http://arxiv.org/pdf/1509.04216v1.pdf **File**

We report on a comparison between space weather events that occurred around the two peaks in the sunspot number (SSN) during solar cycle 24. The two SSN peaks occurred in the years 2012 and 2014. Even though SSN was larger during the second peak, we find that there were more space weather events during the first peak. The space weather events we considered are large solar energetic particle (SEP) events and major geomagnetic storms associated with coronal mass ejections (CMEs). We also considered interplanetary type II radio bursts, which are indicative of energetic CMEs driving shocks. When we compared the CME properties between the two SSN peaks, we find that more energetic CMEs occurred during the 2012 peak. In particular, we find that CMEs accompanying IP type II bursts had an average speed of 1543 km/s during the 2012 peak compared to 1201 km/s during the 2014 peak. This result is consistent with the reduction in the average speed of the general population of CMEs during the second peak. All SEP events were associated with the interplanetary type II bursts, which are better than halo CMEs as indicators of space weather. The comparison between the two peaks also revealed the discordant behavior CME rate and SSN is more pronounced during the second peak. None of the 14 disk-center halo CMEs was associated with a major storm in 2014. The lone major storm in 2014 was due to the intensification of the (southward) magnetic field in the associated magnetic cloud by a shock that caught up and propagated into the magnetic cloud. **23-24 Apr 2012; 18-19 Feb 2014**

Table 2. List of DH-km type II bursts in 2012, the associated CMEs and SEP events

Table 3. List of DH-km type II bursts in 2014, the associated CMEs and SEP events

The Mild Space Weather in Solar Cycle 24

Nat **Gopalswamy**, Sachiko Akiyama, Seiji Yashiro, Hong Xie, Pertti Makela, Grzegorz Michalek

Proc. 14th International Ionospheric Effects Symposium on 'Bridging the gap between applications and research involving ionospheric and space weather disciplines' May 12-14, **2015**, Alexandria, VA

http://arxiv.org/ftp/arxiv/papers/1508/1508.01603.pdf

The space weather is extremely mild during solar cycle 24: the number of major geomagnetic storms and high-energy solar energetic particle events are at the lowest since the dawn of the space age. Solar wind measurements at 1 AU using Wind and ACE instruments have shown that there is a significant drop in the density, magnetic field, total pressure, and Alfven speed in the inner heliosphere as a result of the low solar activity. The drop in large space weather events is disproportionately high because the number of energetic coronal mass ejections that cause these events has not decreased significantly. For example, the rate of halo CMEs, which is a good indicator of energetic CMEs, is similar to that in cycle 23, even though the sunspot number has declined by about 40%. The mild space weather seems to be a consequence of the anomalous expansion of CMEs due to the low ambient pressure in the heliosphere. The anomalous expansion results in the dilution of the magnetic contents of CMEs, so the geomagnetic storms are generally weak. CME driven shocks propagating through the weak heliospheric field are less efficient in accelerating energetic particles, so the particles do not attain high energies. Finally, we would like to point out that extreme events such as the 2012 July 23 CMEs that occurred on the backside of the Sun and did not affect Earth except for a small proton event. **March 17, 2015**

Short term Variability of the Sun Earth System: An Overview of Progress Made during the CAWSES II Period **Review**

Nat **Gopalswamy**, Bruce Tsurutani, Yihua Yan

Progress in Earth and Planetary Science, v. 2, 13, **2015, File**

http://arxiv.org/pdf/1504.06332v1.pdf

This paper presents an overview of results obtained during the CAWSES II period on the short term variability of the Sun and how it affects the near Earth space environment. CAWSES II was planned to examine the behavior of the solar terrestrial system as the solar activity climbed to its maximum phase in solar cycle 24. After a deep minimum following cycle 23, the Sun climbed to a very weak maximum in terms of the sunspot number in cycle 24 (MiniMax24), so many of the results presented here refer to this weak activity in comparison with cycle 23. The short term variability that has immediate consequence to Earth and geospace manifests as solar eruptions from closed field regions and high speed streams from coronal holes. Both electromagnetic (flares) and mass emissions (coronal mass ejections, CMEs) are involved in solar eruptions, while coronal holes result in high speed streams that collide with slow wind forming the so called corotating interaction regions (CIRs). Fast CMEs affect Earth via leading shocks accelerating energetic particles and creating large geomagnetic storms. CIRs and their trailing high speed streams (HSSs), on the other hand, are responsible for recurrent small geomagnetic storms and extended (days) of auroral zone activity, respectively. The latter lead to the acceleration of relativistic magnetospheric killer electrons. One of the major consequences of the weak solar activity is the altered physical state of the heliosphere that has serious implications for the shock-driving and storm causing properties of CMEs. Finally, a discussion is presented on extreme space weather events prompted by the 2012 July 23 super storm event that occurred on the backside of the Sun. Many of these studies were enabled by the simultaneous availability of remote-sensing and in situ observations from multiple vantage points with respect to the Sun Earth line.

TABLE 2 Major geomagnetic storms of cycle 24 (Dst < -100 nT)

Anomalous Expansion of Coronal Mass Ejections during Solar Cycle 24 and its Space Weather Implications

Nat **Gopalswamy**, Sachiko Akiyama, Seiji Yashiro, Hong Xie, and Pertti M?kel?, Grzegorz Michalek

E-print, April **2014**; GRL

The familiar correlation between the speed and angular width of coronal mass ejections (CMEs) is also found in solar cycle 24, but the regression line has a larger slope: for a given CME speed, cycle 24 CMEs are significantly wider than those in cycle 23. The slope change indicates a significant change in the physical state of the heliosphere, due to the weak solar activity. The total pressure in the heliosphere (magnetic + plasma) is reduced by ~40%, which leads to the anomalous expansion of CMEs explaining the increased slope. The excess CME expansion contributes to the diminished effectiveness of CMEs in producing magnetic storms during cycle 24, both because the magnetic content of the CMEs is diluted and also because of the weaker ambient fields. The reduced magnetic field in the heliosphere may contribute to the lack of solar energetic particles accelerated to very high energies during this cycle.

Testing the empirical shock arrival model using quadrature observations

N. **Gopalswamy**1,*, P. Mäkelä, 1,2, H. Xie1,2, S. Yashiro

Space Weather, Volume 11, Issue 11, pages 661–669, November **2013**

http://cdaw.gsfc.nasa.gov/publications/gopal/gopal2013SW_testESA.pdf

The empirical shock arrival (ESA) model was developed based on quadrature data from Helios (in situ) and P-78 (remote sensing) to predict the Sun-Earth travel time of coronal mass ejections (CMEs). The ESA model requires earthward CME speed as input, which is not directly measurable from coronagraphs along the Sun-Earth line. The Solar Terrestrial Relations Observatory (STEREO) and the Solar and Heliospheric Observatory (SOHO) were in quadrature during 2010–2012, so the speeds of Earth-directed CMEs were observed with minimal projection effects. We identified a set of 20 full halo CMEs in the field of view of SOHO that were also observed in quadrature by STEREO. We used the earthward speed from STEREO measurements as input to the ESA model and compared the resulting travel times with the observed ones from L1 monitors. We find that the model predicts the CME travel time within about 7.3 h, which is similar to the predictions by the ENLIL model. We also find that CME-CME and

CME-coronal hole interaction can lead to large deviations from model predictions. **2011 February 15, 2012 July 12**

Table 1. List of shocks detected at L1 and the corresponding halo CMEs observed by SOHO

Table 2. List of events with coronal holes visible on the disk.

Table 3. The number of preceding CMEs within a 24 h interval preceding the CMEs in Table 1

Energetic Particle and Other Space Weather Events of Solar Cycle 24

N. **Gopalswamy**

E-print, Jan 2013, **File**; In Space Weather: The space Radiation Environment, Ed. Q. Hu, G. Li, G. P. Zank, X. Ao, O. Verkhoglyadova, J. H. Adama, AIP Conf Proc. 1500, pp. 14-19, **2012**

We report on the space weather events of solar cycle 24 in comparison with those during a similar epoch in cycle 23. We find major differences in all space weather events: solar energetic particles, geomagnetic storms, and interplanetary shocks. Dearth of ground level enhancement (GLE) events and major geomagnetic storms during cycle 24 clearly standout. The space weather events seem to reflect the less frequent solar eruptions and the overall weakness of solar cycle 24.

TABLE 1. List of large SEP events from solar cycle 24.

2010/08/14; 2011/03/08; 2011/03/21; 2011/06/07; 2011/08/04; 2011/08/09; 2011/09/23; 2011/11/26; 2012/01/23; 2012/01/27; 2012/03/07; 2012/03/13; 2012/05/17; 2012/05/27; 2012/06/16; 2012/07/07; 2012/07/09; 2012/07/12; 2012/07/17; 2012/07/19; 2012/07/23

TABLE 2. Major geomagnetic storms of cycle 24 (Dst < -100 nT)

2011/09/27; 2011/10/25; 2012/03/09; 2012/04/24; 2012/07/15

Solar Radio Bursts and Space Weather

N. **Gopalswamy**

ISWI Workshop, Oct **2012**, Presentation, **File**

Earth-Affecting Solar Causes Observatory (EASCO): A potential International Living with a Star Mission from Sun–Earth L5 ☆

N. **Gopalswamy**, J.M. Davilaa, O.C. St. Cyra, E.C. Sittlera, F. Auchèreb, T.L. Duvall Jr.a, J.T. Hoeksemac, M. Maksimovicd, R.J. MacDowalla, A. Szaboa, M.R. Colliera

Journal of Atmospheric and Solar-Terrestrial Physics, Volume 73, Issues 5–6, April 2011, Pages 658–663

http://www.sciencedirect.com/science/article/pii/S1364682611000149

This paper describes the scientific rationale for an L5 mission and a partial list of key scientific instruments the mission should carry. The L5 vantage point provides an unprecedented view of the solar disturbances and their solar sources that can greatly advance the science behind space weather. A coronagraph and a heliospheric imager at L5 will be able to view CMEs broadsided, so space speed of the Earth-directed CMEs can be measured accurately and their radial structure discerned. In addition, an inner coronal imager and a magnetograph from L5 can give advance information on active regions and coronal holes that will soon rotate on to the solar disk. Radio remote sensing at low frequencies can provide information on shock-driving CMEs, the most dangerous of all CMEs. Coordinated helioseismic measurements from the Sun–Earth line and L5 provide information on the physical conditions at the base of the convection zone, where solar magnetism originates. Finally, in situ measurements at L5 can provide information on the large-scale solar wind structures (corotating interaction regions (CIRs)) heading towards Earth that potentially result in adverse space weather.

Coronal mass ejections and space weather

Nat **Gopalswamy**

Climate and Weather of the Sun-EarthSystem(CAWSES):SelectedPapers from the2007KyotoSymposium,

Edited by T. Tsuda, R. Fujii, K. Shibata, and M. A. Geller, pp. 77–120.

c_TERRAPUB, Tokyo, **2009, File.**

Solar energetic particles (SEPs) and geomagnetic storms are the two primary space weather consequences of coronal mass ejections (CMEs) and their interplanetary counterparts (ICMEs). I summarize the observed properties of CMEs and ICMEs, paying particular attention to those properties that determine the ability of CMEs in causing space weather. Then I provide observational details of two the central issues: (i) for producing geomagnetic storms, the solar source location and kinematics along with the magnetic field structure and intensity are important, and (ii) for SEPs, the shock-driving ability of CMEs, the Alfven speed in the ambient medium, and the connectivity to Earth are crucial parameters.

The Sun and Earth's Space Environment

N. **Gopalswamy**
Proceeding of the 2009 International Conference on Space Science and Communication
26-27 October **2009**, Port Dickson, Negeri Sembilan, Malaysia; **File**
Earth's space environment is closely controlled by solar variability over various time scales. Solar variability is characterized by its output in the form of mass and electromagnetic output. Solar mass emission also interacts with mass entering into the heliosphere in the form of cosmic rays and neutral material. This paper provides an overview of how the solar variability affects Earth's space environment.

Solar Influence on the Heliosphere and Earth's Environment: Recent Progress and Prospects

Proceedings of the ILWS Workshop Goa, India: February 19-24, **2006**
Edited by N. **Gopalswamy** and A. Bhattacharyya
http://cdaw.gsfc.nasa.gov/publications/ilws_goa2006/

Highlights of the October-November 2003 Extreme Events

N. **Gopalswamy**
in "Solar Extreme Events: Fundamental Science and Applied Aspects" ed. A. Chilingarian and G. Karapetyan, Cosmic Ray Division, Alikhanyan Physics Institute, Yerevan, pp. 20-24, **2006**
http://cdaw.gsfc.nasa.gov/publications/gopal/gopal2006SEE_20.pdf
There was a high concentration of coronal mass ejections (CMEs), X-class soft X-ray flares, solar energetic particle (SEP) events, and interplanetary shocks observed during the episode the late October and early November 2003 period. The CMEs were very energetic and the consequences were also unusually intense. These extreme properties were commensurate with the size and energy of the associated active regions. This study suggests that the speed of CMEs may not be much higher than ~3000 km/s, consistent with the large free energy available in the associated active regions. The observations indicate that the CMEs may not have speeds much higher than ~ 3000 km/s implying that the Sun-Earth travel times of CME-driven shocks may not be less than ~0.5 day. Some of the CMEs were both geoeffective and SEPeffective, which are the most important from a space weather point of view.

Space weather observations, modeling, and alerts in support of human exploration of Mars.

Green JL, Dong C, Hesse M, Young CA and Airapetian V
(**2022**) Front. Astron. Space Sci. 9: 1023305.
doi: 10.3389/fspas.2022.1023305
https://www.frontiersin.org/articles/10.3389/fspas.2022.1023305/pdf
Space weather observations and modeling at Mars have begun but they must be significantly increased to support the future of Human Exploration on the Red Planet. A comprehensive space weather understanding of a planet without a global magnetosphere and a thin atmosphere is very different from our situation at Earth so there is substantial fundamental research remaining. It is expected that the development of suitable models will lead to a comprehensive operational Mars space weather alert (MSWA) system that would provide rapid dissemination of information to Earth controllers, astronauts in transit, and those in the exploration zone (EZ) on the surface by producing alerts that are delivered rapidly and are actionable. To illustrate the importance of such a system, we use a magnetohydrodynamic code to model an extreme Carrington-type coronal mass ejection (CME) event at Mars. The results show a significant induced surface field of nearly 3,000 nT on the dayside that could radically affect unprotected electrical systems that would dramatically impact human survival on Mars. Other associated problems include coronal mass ejection (CME) shock-driven acceleration of solar energetic particles producing large doses of ionizing radiation at the Martian surface. In summary, along with working more closely with international partners, the next Heliophysics Decadal Survey must include a new initiative to meet expected demands for space weather forecasting in support of humans living and working on the surface of Mars. It will require significant effort to coordinate NASA and the international community contributions.

Summary of Stakeholder Inputs on Development of a Satellite Anomaly Database From the European Space Weather Week

J. C. **Green**, Y. Y. Shprits, E. Haggarty, T. Onsager, I. Zhelavskaya
Space Weather Volume16, Issue4 April **2018** Pages 343-344
http://sci-hub.tw/https://onlinelibrary.wiley.com/doi/abs/10.1029/2018SW001823
Stakeholders met at the recent European Space Weather Week to discuss the development of a satellite anomaly database. This summary reviews the presentations and suggestions given at the discussion session. Presenters

reviewed ongoing international efforts to collect and distribute satellite anomaly information. Well-defined suggestions were given for different possible frameworks. Group discussion after suggested that a way forward would be to first demonstrate the utility of an anomaly database with available public anomaly information. More discussion is needed to define the exact framework for future implementation.

The origin, early evolution and predictability of solar eruptions **Review**

Lucie **Green**, Tibor Torok, Bojan Vrsnak, Ward Manchester IV, Astrid Veronig

Space Science Reviews **2018**

https://arxiv.org/pdf/1801.04608.pdf **File**

Coronal mass ejections (CMEs) were discovered in the early 1970s when space-borne coronagraphs revealed that eruptions of plasma are ejected from the Sun. Today, it is known that the Sun produces eruptive flares, filament eruptions, coronal mass ejections and failed eruptions; all thought to be due to a release of energy stored in the coronal magnetic field during its drastic reconfiguration. This review discusses the observations and physical mechanisms behind this eruptive activity, with a view to making an assessment of the current capability of forecasting these events for space weather risk and impact mitigation. Whilst a wealth of observations exist, and detailed models have been developed, there still exists a need to draw these approaches together. In particular more realistic models are encouraged in order to asses the full range of complexity of the solar atmosphere and the criteria for which an eruption is formed. From the observational side, a more detailed understanding of the role of photospheric flows and reconnection is needed in order to identify the evolutionary path that ultimately means a magnetic structure will erupt. **19 Oct 1994, 19 July 2000, 4th January 2002, 13 Feb 2009**

Impact of Space Weather on the Satellite Industry **Review**

J.C. **Green**1 , J. Likar2 and Yuri Shprits3,

Space Weather, 15, 804–818, **2017** doi:10.1002/2017SW001646.

Space Weather Quarterly, 14, Issue 3, pp. 18-32 http://onlinelibrary.wiley.com/doi/10.1002/swq.15/epdf

http://sci-hub.cc/10.1002/2017SW001646

This paper describes space weather impacts to the satellite infrastructure as perceived by satellite industry stakeholders. The information was gathered through in-person and remote meetings with both satellite operators and manufacturers. The paper describes current impacts, industry processes for managing and mitigating impacts, costs, and industry needs and requirements. Lastly, we suggest potential improvements and solutions to problem areas based on our observation of the industry processes including 1) Improved tools for quick anomaly attribution, 2) Training, and 3) Coordinated information sharing.

Multiple-Hour-Ahead Forecast of the Dst Index Using a Combination of Long Short-Term Memory Neural Network and Gaussian Process

M. A. **Gruet**, M. Chandorkar, A. Sicard, E. Camporeale

Space Weather **Volume16, Issue11** Pages 1882-1896 **2018**

http://sci-hub.tw/10.1029/2018SW001898

In this study, we present a method that combines a Long Short-Term Memory (LSTM) recurrent neural network with a Gaussian process (GP) model to provide up to 6-hr-ahead probabilistic forecasts of the Dst geomagnetic index. The proposed approach brings together the sequence modeling capabilities of a recurrent neural network with the error bars and confidence bounds provided by a GP. Our model is trained using the hourly OMNI and Global Positioning System (GPS) databases, both of which are publicly available. We first develop a LSTM network to get a single-point prediction of Dst. This model yields great accuracy in forecasting the Dst index from 1 to 6 hr ahead, with a correlation coefficient always higher than 0.873 and a root-mean-square error lower than 9.86. However, even if global metrics show excellent performance, it remains poor in predicting intense storms (Dst < -250 nT) 6 hr in advance. To improve it and to obtain probabilistic forecasts, we combine the LSTM model obtained with a GP and evaluate the hybrid predictor using the receiver operating characteristic curve and the reliability diagram. We conclude that this hybrid methodology provides improvements in the forecast of geomagnetic storms, from 1 to 6 hr ahead.

The Use of Ensembles in Space Weather Forecasting Meeting Report

J.A. **Guerra** , S.A. Murray , E. Doornbos

Space Weather **Volume18, Issue2** e2020SW002443 **2020**

sci-hub.si/10.1029/2020SW002443

https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020SW002443

In order to advance the use of ensembles in forecasting space weather events, the workshop Ensemble Forecasts in Space Weather: Science and Operations took place at the Lorentz Center in Leiden, The Netherlands, on September 2-6, 2019. The aim of this workshop was to bring together space weather scientists from academic institutions and operational centers, and experts in ensemble techniques in terrestrial weather forecasting. Ensembles are currently used across all the subfields of space weather, however, there seems to be no community-wide consensus about how to best utilize them. Therefore, the Testing, Understanding, and Leveraging Ensemble Predictions for Space Weather (TULEPS) working group was created to provide a starting point for the space weather community to the use of ensemble techniques. See https://www.lorentzcenter.nl/lc/web/2019/1195/info.php3?wsid=1195

Everyday space weather **Review**

Madhulika **Guhathakurta***
J. Space Weather Space Clim. **2021**, 11, 36
https://www.swsc-journal.org/articles/swsc/pdf/2021/01/swsc210009.pdf
https://doi.org/10.1051/swsc/2021019
Big events, however, are not the only events. Contrary to popular belief, there is such a thing as "everyday space weather," and it is more pervasive than you might suppose (Schrijver, 2015).

Interplanetary Space Weather: A New Paradigm

Madhulika **Guhathakurta**
Eos, Transactions AGU, 30 April **2013**, Volume 94, Issue 18, Pages 165–172
http://onlinelibrary.wiley.com/doi/10.1002/2013EO180001/pdf
Until recently, operators of distant missions generally had no clue when a solar storm was about to engulf their spacecraft. Forecasters could barely predict space weather in the vicinity of Earth; forecasts for other parts of the solar system were even more challenging. This is not the case anymore. During the St. Patrick's Day storms, most mission operators knew the storms were coming and had opportunities to take protective action. This signals a new paradigm in space weather forecasting: The discipline is now becoming interplanetary.

The International SpaceWeather Initiative (ISWI)

Madhulika **Guhathakurta**, Joseph M. Davila, and Nat Gopalswamy
SPACE WEATHER, VOL. 11, 327–329, doi:10.1002/swe.20048, **2013**
http://onlinelibrary.wiley.com/doi/10.1002/swe.20058/pdf
A simple new category system for CMEs based on frequency of detection and speed
Applicable in space weather operations and research

Predicting the Loci of Solar Eruptions

N. **Gyenge**, R. Erdélyi
2017 Space Weather of the Heliosphere: Processes and Forecasts Proceedings IAU Symposium No. 335
https://arxiv.org/pdf/1710.06196.pdf
The longitudinal distribution of solar active regions shows non-homogeneous spatial behaviour, which is often referred to as Active Longitude (AL). Evidence for a significant statistical relationships between the AL and the longitudinal distribution of flare and coronal mass ejections (CME) occurrences is found in Gyenge et al, 2017 (ApJ, 838, 18). The present work forecasts the spatial position of AL, hence the most flare/CME capable active regions are also predictable. Our forecast method applies Autoregressive Integrated Moving Average model for the next 2 years time period. We estimated the dates when the solar flare/CME capable longitudinal belts face towards Earth.

Active longitude and CME occurrences

N. **Gyenge**, T. Singh, T. S. Kiss, A. K. Srivastava, R. Erdélyi
2017
https://arxiv.org/pdf/1702.06664.pdf
The spatial inhomogeneity of the distribution of coronal mass ejection (CME) occurrences in the solar atmosphere could provide a tool to estimate the longitudinal position of the most probable CME-capable active regions in the Sun. The anomaly in the longitudinal distribution of active regions themselves is often referred to as active longitude (AL). In order to reveal the connection between the AL and CME spatial occurrences, here we investigate the morphological properties of active regions. The first morphological property studied is the separateness parameter, which is able to characterise the probability of the occurrence of an energetic event, such as solar flare or CME. The second morphological property is the sunspot tilt angle. The tilt angle of sunspot groups allows us to estimate the helicity of active regions. The increased helicity leads to a more complex built-up of the magnetic structure and also can cause CME eruption. We found that the most complex active regions appear near to the AL and the AL itself is associated with the most tilted active regions. Therefore, the number of CME occurrences is higher within the AL. The origin of the fast CMEs is also found to be associated with this region. We concluded that the source of the most probably CME-capable active regions is at the AL. By applying this method we can potentially forecast a flare

and/or CME source several Carrington rotations in advance. This finding also provides new information for solar dynamo modelling.
0/03/2011, 25/06/2011, 07/03/2012

Active Longitude and Solar Flare Occurrences

N. **Gyenge**, A. Ludmány, T. Baranyi
2016
http://arxiv.org/pdf/1512.08124v1.pdf
The aim of the present work is to specify the spatio-temporal characteristics of flare activity observed by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) and Geostationary Operational Environmental Satellite (GOES) satellites in connection with the behaviour of the longitudinal domain of enhanced sunspot activity known as active longitude (AL). By using our method developed for this purpose, we identified the AL in every Carrington Rotation provided by the Debrecen Photoheliographic Data (DPD). The spatial probability of flare occurrence has been estimated depending on the longitudinal distance from AL in the northern and southern hemispheres separately. We have found that more than the 60\% of the RHESSI and GOES flares is located within ±36∘ from the active longitude. Hence, the most flare-productive active regions tend to be located in or close to the active longitudinal belt. This observed feature may allow predicting the geo-effective position of the domain of enhanced flaring probability. Furthermore, we studied the temporal properties of flare occurrence near the active longitude and several significant fluctuations were found. More precisely, the results of the method are the following fluctuations: 0.8 years, 1.3 years and 1.8 years. These temporal and spatial properties of the solar flare occurrence within the active longitudinal belts could provide us enhanced solar flare forecasting opportunity.

A Deep-Learning Approach for Operation of an Automated Realtime Flare Forecast

Yuko **Hada-Muranushi**, Takayuki Muranushi, Ayumi Asai, Daisuke Okanohara, Rudy Raymond, Gentaro Watanabe, Shigeru Nemoto, Kazunari Shibata
Space Weather **2016**
http://arxiv.org/pdf/1606.01587v1.pdf
Automated forecasts serve important role in space weather science, by providing statistical insights to flare-trigger mechanisms, and by enabling tailor-made forecasts and high-frequency forecasts. Only by realtime forecast we can experimentally measure the performance of flare-forecasting methods while confidently avoiding overlearning. We have been operating unmanned flare forecast service since **August, 2015** that provides 24-hour-ahead forecast of solar flares, every 12 minutes. We report the method and prediction results of the system.

Mechanisms for solar influence on the Earth's climate

J. D. **Haigh**
Climate and Weather of the Sun-Earth System (CAWSES): Selected Papers from the 2007 Kyoto Symposium,
Edited by T. Tsuda, R. Fujii, K. Shibata, and M. A. Geller, pp. 231-256.
© by TERRAPUB, Tokyo, **2009**.
[Full text] (PDF 3.9 MB)

Toward GIC Forecasting: Statistical Downscaling of the Geomagnetic Field to Improve Geoelectric Field Forecasts

C. Haines, M. J. Owens, L. Barnard, M. Lockwood, C. D. Beggan, A. W. P. Thomson, N. C. Rogers
Space Weather Volume20, Issue1 January **2022** e2021SW002903
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021SW002903
https://doi.org/10.1029/2021SW002903
Geomagnetically induced currents (GICs) are an impact of space weather that can occur during periods of enhanced geomagnetic activity. GICs can enter into electrical power grids through earthed conductors, potentially causing network collapse through voltage instability or damaging transformers. It would be beneficial for power grid operators to have a forecast of GICs that could inform decision making on mitigating action. Long lead-time GIC forecasting requires magnetospheric models as drivers of geoelectric field models. However, estimation of the geoelectric field is sensitive to high-frequency geomagnetic field variations, which operational global magneto-hydrodynamic models do not fully capture. Furthermore, an assessment of GIC forecast uncertainty would require a large ensemble of magnetospheric runs, which is computationally expensive. One solution that is widely used in climate science is “downscaling,” wherein sub-grid variations are added to model outputs on a statistical basis. We present proof-of-concept results for a method that temporally downscales low-resolution magnetic field data on a 1-hr timescale to 1-min resolution, with the hope of improving subsequent geoelectric field magnitude estimates. An analog ensemble (AnEn) approach is used to select similar hourly averages in a historical data set, from which we separate the high-resolution perturbations to add to the hourly average values. We find that AnEn outperforms the

benchmark linear-interpolation approach in its ability to accurately drive an impacts model, suggesting GIC forecasting would be improved. We evaluated the ability of AnEn to predict extreme events using the FSS, HSS, cost/loss analysis and BSS, finding that AnEn outperforms the "do-nothing" approach. **4 Feb 1983, 14 Dec 2006**

Intense Geomagnetically Induced Currents (GICs): Association with Solar and Geomagnetic Activities

Rajkumar **Hajra**

Solar Physics volume 297, Article number: 14 (**2022**)

https://link.springer.com/content/pdf/10.1007/s11207-021-01945-8.pdf

https://doi.org/10.1007/s11207-021-01945-8

We present a statistical study of the intense geomagnetically induced currents (GICs) in the subauroral region, which can damage ground electronic systems. From the natural gas pipeline recordings taken near Mäntsälä, Finland (geographic: 60.6∘60.6∘N, 25.2∘25.2∘E), 605 GICs with peak intensity >10 A were registered from 1999 through 2019, ≈2 solar cycles. During Solar Cycle 23, the occurrence peak was observed during the solar maximum with fewer events during the descending phase and no events during the solar minimum. Overall a lower occurrence rate was recorded during Solar Cycle 24. There was an asymmetric semi-annual variation of events with a larger number during September–November than during March–April, and the lowest occurrence around the Summer solstice. While only one event was recorded during geomagnetic quiet conditions (SYM-H >−50 nT), ≈2% of all events were associated with moderate (−50 nT > SYM-H ≥−100 nT), ≈31% with intense (−100 nT > SYM-H ≥−250 nT), and ≈67% with superintense (SYM-H <−250 nT) geomagnetic storms. Among these, ≈72% occurred in the storm main phase and ≈28% in the recovery phase. Interplanetary sheaths are found to be the most efficient events causing the majority (≈50.8%) of the GICs with peak intensity >10 A followed by magnetic clouds (≈44.0%), corotating interaction regions (≈3.1%), fast forward shocks following the sheaths (≈1.9%), and solar wind high-speed streams (≈0.2%). **7 – 8 November 2004**

Application usability levels: a framework for tracking project product progress

Alexa J. **Halford**1*, Adam C. Kellerman2, Katherine Garcia-Sage3,4, Jeffrey Klenzing4, Brett A. Carter5, Ryan M. McGranaghan6,7, Timothy Guild1 et al.

J. Space Weather Space Clim. **2019**, 9, A34

https://www.swsc-journal.org/articles/swsc/pdf/2019/01/swsc190028.pdf

The space physics community continues to grow and become both more interdisciplinary and more intertwined with commercial and government operations. This has created a need for a framework to easily identify what projects can be used for specific applications and how close the tool is to routine autonomous or on-demand implementation and operation. We propose the Application Usability Level (AUL) framework and publicizing AULs to help the community quantify the progress of successful applications, metrics, and validation efforts. This framework will also aid the scientific community by supplying the type of information needed to build off of previously published work and publicizing the applications and requirements needed by the user communities. In this paper, we define the AUL framework, outline the milestones required for progression to higher AULs, and provide example projects utilizing the AUL framework. This work has been completed as part of the activities of the Assessment of Understanding and Quantifying Progress working group which is part of the International Forum for Space Weather Capabilities Assessment.

A New Model for Nowcasting the Aviation Radiation Environment With Comparisons to In Situ Measurements During GLEs

A. D. P. **Hands**, F. Lei, C. S. Davis, B. J. Clewer, C. S. Dyer, K. A. Ryden

Space Weather Volume20, Issue8 e2022SW003155 **2022**

https://doi.org/10.1029/2022SW003155

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022SW003155

Significant increases to the atmospheric radiation environment are recorded by a network of ground level neutron monitors as ground level enhancements (GLEs). These space weather phenomena pose a risk to aviation via single event effects in aircraft electronics and ionizing dose to passengers and crew. Under the UK Space Weather Instrumentation, Measurement, Modeling and Risk programme, we have developed a new model to provide nowcasts of the aviation radiation environment, including both the galactic cosmic ray (GCR) background and during GLE events. The Model for Atmospheric Ionising Radiation Effects (MAIRE+) uses multiple data sources to characterize primary GCR and GLE particle spectra and combines these with precalculated geomagnetic and atmospheric response matrices to predict particle fluxes from ground level to 20 km altitude across the entire globe. Two European neutron monitors (located at Oulu in Finland and Dourbes in Belgium) are used as the primary indicators of GLE intensity in order to maximize accuracy over UK airspace. Outputs from MAIRE+ for the historical GLEs in September and October 1989 are compared to recalibrated empirical data from a solid-state detector that was carried on Concorde in that period. The model will be hosted in the UK and will provide additional capability to the Met Office Space Weather Operations Center (MOSWOC). **29 Sep, 19 Oct, 24 Oct 1989; 10 Sep 2017, 28 Oct 2021, 4-5 Nov 2021**

Radiation Effects on Satellites During Extreme Space Weather Events

A. D. P. **Hands**, K. A. Ryden, N. P. Meredith, S. A. Glauert, R. B. Horne

Space Weather Volume16, Issue9 September **2018** Pages 1216-1226

sci-hub.tw/10.1029/2018sw001913

High-energy trapped electrons in the Van Allen belts pose a threat to the survivability of orbiting spacecraft. Two key radiation effects are total ionizing dose and displacement damage dose in components and materials, both of which cause cumulative and largely irreversible damage. During an extreme space weather event, trapped electron fluxes in the Van Allen belts can increase by several orders of magnitude in intensity, leading to an enhanced risk of satellite failure. We use extreme environments generated by modeling and statistical analyses to estimate the consequences for satellites in terms of the radiation effects described above. A worst-case event could lead to significant losses in power generating capability—up to almost 8%—and cause up to four years' worth of ionizing dose degradation, leading to component damage and a life-shortening effect on satellites. The consequences of such losses are hugely significant given our increasing reliance on satellites for a vast array of services, including communication, navigation, defense, and critical infrastructure.

The Sun and SpaceWeather

Arnold **Hanslmeier**

2010, In: Gopalswamy, N., Hasan, S.S., Ambastha, A. (eds.)

Heliophysical Processes, Astrophysics and Space Science Proceedings, Springer, Berlin, p. 233-249,

File

In this chapter we will briefly review the basic interactions between particles and magnetic fields, the processes that occur on the Sun which are relevant for space weather as well as their influences on Earth and the space environment of Earth. The strong societal impact of space weather to our complex world of telecommunication will be stressed.

SpaceX – sailing close to the space weather?

Mike **Hapgood**, Huixin Liu, Noé Lugaz

Space Weather e2022SW003074 **2022**

https://doi.org/10.1029/2022SW003074

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022SW003074

The **3 February 2022** launch of 49 of SpaceX's Starlink satellites has provided a fascinating example of how even modest space weather can have significant practical and financial consequences. Enhanced atmospheric drag associated with a minor geomagnetic storm led to the loss of the majority of the 49 launched satellites. Although the 36th launch by SpaceX in the past 3 years, it was the first that experienced stormy space weather. We expect more stormy space weather as Solar Cycle 25 ramps up towards its peak expected in 2025. A subsequent Starlink launch on **21 February** used a higher initial orbit at 300km, reducing the payload from 49 to 46 satellites, and can be considered an agile response to the space weather losses experienced two weeks earlier. Lessons to be learnt by the space industry and the space weather community are discussed, including a better dialogue, nuanced understanding of space weather risks associated with modest events, but also an opportunity to investigate the space environment in relatively unexplored regions such as very low and high low Earth orbits.

Development of Space Weather Reasonable Worst Case Scenarios for the UK National Risk Assessment ***Можно рассматривать как* Review *по космической погоде***

Mike **Hapgood** , Matthew J. Angling , Gemma Attrill , Mario Bisi , Paul S. Cannon , Clive Dyer , Jonathan P. Eastwood , Sean Elvidge , Mark Gibbs , Richard A. Harrison … See all authors

Space Weather e2020SW002593 **2021**

https://doi.org/10.1029/2020SW002593

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020SW002593

Severe space weather was identified as a risk to the UK in 2010 as part of a wider review of natural hazards triggered by the societal disruption caused by the eruption of the Eyjafjallajökull volcano in April of that year. To support further risk assessment by government officials, and at their request, we developed a set of reasonable worst-case scenarios and first published them as a technical report in 2012 (current version published in 2020). Each scenario focused on a space weather environment that could disrupt a particular national infrastructure such as electric power or satellites, thus enabling officials to explore the resilience of that infrastructure against severe space weather through discussions with relevant experts from other parts of government and with the operators of that infrastructure. This approach also encouraged us to focus on the environmental features that are key to generating adverse impacts. In this paper, we outline the scientific evidence that we have used to develop these scenarios, and the refinements made to them as new evidence emerged. We show how these scenarios are also considered as an ensemble so that government officials can prepare for a severe space weather event, during which many or all of the different scenarios will materialise. Finally, we note that this ensemble also needs to include insights into how public behaviour will play out during a severe space weather event and hence the importance of providing robust, evidence-based information on space weather and its adverse impacts. **12 November 1960**

2 Geomagnetically induced currents
3 Ionospheric impacts on radio systems
4 Space weather impacts on satellite operations
5 Space weather and atmospheric radiation
6 Solar Radio Burst impacts on radio systems

The Great Storm of May 1921: An Exemplar of a Dangerous Space Weather Event

Mike **Hapgood**

Space Weather **2019**

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019SW002195

We reconstruct the timeline of the extreme space weather event of May 1921, reviewing a wealth of reports from scientific literature, databases, newspaper reports, and reports by historians and astronomers. A series of coronal mass ejections (CMEs) bombarded Earth between 13 and 16 May, as shown by a series of sudden commencements observed across the global network of magnetometers. These CMEs produced three major periods of geomagnetic activity. The first period followed the arrival of two CMEs on 13 May. These may have cleared much density from the inner heliosphere, enabling a subsequent CME to travel quickly to Earth and cause intense activity. Continuing moderate magnetic activity following the first period may also have preconditioned the magnetosphere so it responded strongly to that later CME. This arrived late on 14 May, driving a short period of very intense activity early on 15 May, including technological impacts indicative of strong geoelectric fields. Another CME arrived early on 16 May, driving intense activity similar to that on 13 May. We show how these impacts fit with scientific observations to give a timeline that can be used in worst-case studies/benchmarks. We also show that some impacts were probably coincidental with the storm, but due to more prosaic faults. This sequence of preconditioning, intense geoelectric fields, and their impacts, plus coincidental faults, makes the 1921 event an excellent basis for building space weather scenarios. Such scenarios are vital scientific input to the development and implementation of policies for mitigation of severe space weather.

Chapter 1 - Linking Space Weather Science to Impacts—The View From the Earth

Mike **Hapgood**

In: Extreme Events in Geospace

Origins, Predictability, and Consequences **Book**

Editor: Natalia **Buzulukova**, Elsevier, **2018**, 798 p. **File**

Pages 3-34 https://doi.org/10.1016/B978-0-12-812700-1.00001-7

This chapter explores how we can link space weather science to impacts. It stresses the value of tracing space weather from its societal impacts on human activities on Earth back to its origin on the Sun, thus enabling us to more clearly identify the solar, heliospheric, and terrestrial phenomena that are crucial to assessing and forecasting the societal impacts of space weather. The chapter also presents a structure that consolidates most space weather impacts into four major topics: (1) the geoelectric fields that drive geomagnetically induced currents; (2) the complex behavior of the upper atmosphere and its seemingly diverse impacts on radio systems and satellite orbits; (3) the atmospheric radiation that increasingly disrupts digital devices, both on aircraft and on the ground; and (4) the interaction of satellites with the rich plasma environments that fill many operational orbits, not least the vital geosynchronous ring. This focus on major topics provides a way of simplifying the links between science and impacts, which can otherwise appear as a long and complex list of impact areas that risk being boring and confusing because of the diversity of space weather effects. It facilitates an understanding of how the science links to impacts—especially in extreme space weather conditions. In a final section we look to the future and consider how space weather risks may evolve. We review a number of technological developments that may change our perception of space weather risks in the next few decades. This includes areas in which new technologies may open up new space weather risks as well as areas in which new technologies may retire current space weather risks.

Space Weather small **Book**

Hapgood M.

2017. Bristol, UK: IOP Publishing. (doi:10.1088/978-0-7503-1372-8)

https://iopscience.iop.org/book/978-0-7503-1372-8.pdf

Space weather—changes in the Earth's environment that can often be traced to physical processes in the Sun—can have a profound impact on critical Earth-based infrastructures such as power grids and civil aviation. Violent eruptions on the solar surface can eject huge clouds of magnetized plasma and particle radiation, which then propagate across interplanetary space and envelop the Earth. These space weather events can drive major changes in a variety of terrestrial environments, which can disrupt, or even damage, many of the technological systems that underpin modern societies. The aim of this book is to offer an insight into our current scientific understanding of space weather, and how we can use that knowledge to mitigate the risks it poses for Earth-based technologies. It also identifies some key challenges for future space-weather research, and considers how emerging technological developments may introduce new risks that will drive continuing investigation.

L1L5Together: Report of Workshop on Future Missions to Monitor Space Weather on the Sun and in the Solar Wind Using Both the L1 and L5 Lagrange Points as Valuable Viewpoints

Mike **Hapgood**

Space Weather Volume 15, Issue 5 May **2017** Pages 654–657

http://sci-hub.cc/10.1002/2017SW001652

The "L5 in Tandem with L1: Future Space Weather Missions Workshop" was held in London on 6–9 March 2017 to discuss technical and programmatic steps toward an operational system for monitoring space weather conditions on the Sun and in the solar wind. This system would exploit the viewpoints provided by the Sun-Earth L1 and L5 Lagrange points—two locations where we can place spacecraft in quasi-stable orbits with complementary views of solar and interplanetary conditions that could lead to adverse space-weather impacts at Earth. This personal report summarizes the talks and discussions at the workshop—pulling out key issues of likely interest to a wider audience and important considerations on the route to an operational system at L1 and L5, a system that can help to protect societies around the world from the risks posed by space weather.

The application of heliospheric imaging to space weather operations: Lessons learned from published studies **Review**

Richard A. **Harrison**, Jackie A. Davies, Doug Biesecker, Mark Gibbs

Space Weather Volume 15, Issue 8 August **2017** Pages 985–1003

http://onlinelibrary.wiley.com/doi/10.1002/2017SW001633/full

http://onlinelibrary.wiley.com/doi/10.1002/2017SW001633/epdf

The field of heliospheric imaging has matured significantly over the last 10 years—corresponding, in particular, to the launch of NASA's STEREO mission and the successful operation of the heliospheric imager (HI) instruments thereon. In parallel, this decade has borne witness to a marked increase in concern over the potentially damaging effects of space weather on space and ground-based technological assets, and the corresponding potential threat to human health, such that it is now under serious consideration at governmental level in many countries worldwide. Hence, in a political climate that recognizes the pressing need for enhanced operational space weather monitoring capabilities most appropriately stationed, it is widely accepted, at the Lagrangian L1 and L5 points, it is timely to assess the value of heliospheric imaging observations in the context of space weather operations. To this end, we review a cross section of the scientific analyses that have exploited heliospheric imagery—particularly from STEREO/HI—and discuss their relevance to operational predictions of, in particular, coronal mass ejection (CME) arrival at Earth and elsewhere. We believe that the potential benefit of heliospheric images to the provision of accurate CME arrival predictions on an operational basis, although as yet not fully realized, is significant and we assert that heliospheric imagery is central to any credible space weather mission, particularly one located at a vantage point off the Sun-Earth line. **1 August 2010, 15 Feb 2011, 8 March 2012, 5 March 2013, 20-27 May 2017**

SpaceX—Sailing Close to the Space Weather?

Mike **Hapgood**, Huixin Liu, Noé Lugaz

Space Weather Volume20, Issue3 March **2022** e2022SW003074

https://doi.org/10.1029/2022SW003074

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022SW003074

The **3 February 2022** launch of 49 of SpaceX's Starlink satellites has provided a fascinating example of how even modest space weather can have significant practical and financial consequences. Enhanced atmospheric drag associated with a minor geomagnetic storm led to the loss of the majority of the 49 launched satellites. Although the 36th launch by SpaceX in the past 3 years, it was the first that experienced stormy space weather. We expect more stormy space weather as Solar Cycle 25 ramps up toward its peak expected in 2025. A subsequent Starlink launch on **21 February** used a higher initial orbit at 300 km, reducing the payload from 49 to 46 satellites, and can be considered an agile response to the space weather losses experienced 2 weeks earlier. Lessons to be learned by the space industry and the space weather community are discussed, including a better dialog, nuanced understanding of space weather risks associated with modest events, but also an opportunity to investigate the space environment in relatively unexplored regions such as very low and high low Earth orbits.

Development of Space Weather Reasonable Worst Case Scenarios for the UK National Risk Assessment *Можно рассматривать как* **Review** *по космической погоде*

Mike **Hapgood** , Matthew J. Angling , Gemma Attrill , Mario Bisi , Paul S. Cannon , Clive Dyer , Jonathan P. Eastwood , Sean Elvidge , Mark Gibbs , Richard A. Harrison … See all authors

Space Weather Volume19, Issue4 e2020SW002593 April **2021**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020SW002593
https://doi.org/10.1029/2020SW002593

Severe space weather was identified as a risk to the UK in 2010 as part of a wider review of natural hazards triggered by the societal disruption caused by the eruption of the Eyjafjallajökull volcano in April of that year. To support further risk assessment by government officials, and at their request, we developed a set of reasonable worst-case scenarios and first published them as a technical report in 2012 (current version published in 2020). Each scenario focused on a space weather environment that could disrupt a particular national infrastructure such as electric power or satellites, thus, enabling officials to explore the resilience of that infrastructure against severe space weather through discussions with relevant experts from other parts of government and with the operators of that infrastructure. This approach also encouraged us to focus on the environmental features that are key to generating adverse impacts. In this paper, we outline the scientific evidence that we have used to develop these scenarios, and the refinements made to them as new evidence emerged. We show how these scenarios are also considered as an ensemble so that government officials can prepare for a severe space weather event, during which many or all of the different scenarios will materialize. Finally, we note that this ensemble also needs to include insights into how public behavior will play out during a severe space weather event and hence the importance of providing robust, evidence-based information on space weather and its adverse impacts. **November 12, 1960**

The Great Storm of May 1921: an Exemplar of a Dangerous Space Weather Event

Mike **Hapgood**

Space Weather **2019**
sci-hub.se/10.1029/2019SW002195

We re-construct the timeline of the extreme space weather event of May 1921, reviewing a wealth of reports from scientific literature, databases, newspaper reports, and reports by historians and astronomers. A series of coronal mass ejections (CMEs) bombarded Earth **between 13 and 16 May**, as shown by a series of sudden commencements observed across the global network of magnetometers. These CMEs produced three major periods of geomagnetic activity. The first period followed the arrival of two CMEs on 13 May. These may have cleared much density from the inner heliosphere, enabling a subsequent CME to travel quickly to Earth and cause intense activity. Continuing moderate magnetic activity following the first period may also have preconditioned the magnetosphere so it responded strongly to that later CME. This arrived late on 14 May, driving a short period of very intense activity early on 15 May, including technological impacts indicative of strong geoelectric fields. Another CME arrived early on 16 May, driving intense activity similar to that on 13 May. We show how these impacts fit with scientific observations to give a timeline that can be used in worst case studies/benchmarks. We also show that some impacts were probably coincidental with the storm, but due to more prosaic faults. This sequence of preconditioning, intense geoelectric fields and their impacts, plus coincidental faults, makes the 1921 event an excellent basis for building space weather scenarios. Such scenarios are vital scientific input to the development and implementation of policies for mitigation of severe space weather.

Chapter 1 - Linking Space Weather Science to Impacts—The View From the Earth **Review**

Mike **Hapgood**

In: Extreme Events in Geospace Origins, Predictability, and Consequences
2018, Pages 3-34
http://sci-hub.tw/10.1016/B978-0-12-812700-1.00001-7

This chapter explores how we can link space weather science to impacts. It stresses the value of tracing space weather from its societal impacts on human activities on Earth back to its origin on the Sun, thus enabling us to more clearly identify the solar, heliospheric, and terrestrial phenomena that are crucial to assessing and forecasting the societal impacts of space weather. The chapter also presents a structure that consolidates most space weather impacts into four major topics: (1) the geoelectric fields that drive geomagnetically induced currents; (2) the complex behavior of the upper atmosphere and its seemingly diverse impacts on radio systems and satellite orbits; (3) the atmospheric radiation that increasingly disrupts digital devices, both on aircraft and on the ground; and (4) the interaction of satellites with the rich plasma environments that fill many operational orbits, not least the vital geosynchronous ring. This focus on major topics provides a way of simplifying the links between science and

impacts, which can otherwise appear as a long and complex list of impact areas that risk being boring and confusing because of the diversity of space weather effects. It facilitates an understanding of how the science links to impacts—especially in extreme space weather conditions. In a final section we look to the future and consider how space weather risks may evolve. We review a number of technological developments that may change our perception of space weather risks in the next few decades. This includes areas in which new technologies may open up new space weather risks as well as areas in which new technologies may retire current space weather risks.
March 13, 1989

Towards a scientific understanding of the risk from extreme space weather

M.A. **Hapgood**

Advances in Space Research 47 (**2011**) 2059–2072

Like all natural hazards, space weather exhibits occasional extreme events over timescales of decades to centuries. Historical events provoked much interest, and sometimes alarm, because bright aurora becomes visible at mid-latitudes. However, they had little economic impact because the major technologies of those eras were not sensitive to space weather. This is no longer true. The widespread adoption of advanced technological infrastructures over the past 40 years has created significant sensitivity. So these events now have the potential to disrupt those infrastructures – and thus have profound economic and societal impact. However, like all extreme hazards, such events are rare, so we have limited data on which to build our understanding of the events. This limitation is uniquely serious for space weather since it is a global phenomenon. Many other natural hazards (e.g. flash floods) are highly localised, so statistically significant datasets can be assembled by combining data from independent instances of the hazard recorded over a few decades. Such datasets are the foundation on which reliable risk assessment methodologies are built. But we have a single instance of space weather so we would have to make observations for many centuries in order to build a statistically significant dataset. We show that it is not practicable to assess the risk from extreme events using simple statistical methods. Instead we must exploit our knowledge of solar-terrestrial physics to find other ways to assess these risks. We discuss three alternative approaches: (a) use of proxy data, (b) studies of other solar systems, and (c) use of physics-based modelling. We note that the proxy data approach is already well-established as a technique for assessing the long-term risk from radiation storms, but does not yet provide any means to assess the risk from severe geomagnetic storms. This latter risk is more suited to the other approaches, but significant research is needed to make progress. We need to develop and expand techniques to monitoring key space weather features in other solar systems (stellar flares, radio emissions from planetary aurorae). And to make progress in modelling severe space weather, we need to focus on the physics that controls severe geomagnetic storms, e.g. how can dayside and tail reconnection be modulated to expand the region of open flux to envelop mid-latitudes?

Space Weather on the Surface of Mars: Impact of the September 2017 Events

D. M. **Hassler**, C. Zeitlin, B. Ehresmann, R. F. Wimmer-Schweingruber, J. Guo, D. Matthiä, S. Rafkin, T. Berger , G. Reitz

Space Weather **Volume16, Issue11** Pages 1702-1708 **2018**

http://sci-hub.tw/10.1029/2018SW001959

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2018SW001959

Although solar activity is declining as the Sun approaches solar minimum, a series of large solar storms occurred in September 2017 that impacted both Earth and Mars. This was the largest event seen on the surface of Mars by the Radiation Assessment Detector (RAD) on the Mars Science Laboratory (MSL) Curiosity rover since landing in 2012, and was also observed as GLE72 on Earth, making it the first event observed to produce a Ground Level Enhancement (GLE) on 2 planets at the same time. We present RAD observations of the surface radiation environment since 2012, and discuss the impact of the September 2017 events on this environment, and its implications for human exploration and for mitigating the risk of space radiation and space weather events for future manned missions to Mars.

The Extreme Space Weather Event in 1941 February/March

Hisashi **Hayakawa**1,2,3,4, Sean P. Blake5,6, Ankush Bhaskar5,6,7, Kentaro Hattori8, Denny M. Oliveira5,9, and Yusuke Ebihara1

2021 ApJ 908 209

https://arxiv.org/ftp/arxiv/papers/2010/2010.00452.pdf

https://doi.org/10.3847/1538-4357/abb772

Given the infrequency of extreme geomagnetic storms, it is significant to note the concentration of three extreme geomagnetic storms in 1941, whose intensities ranked fourth, twelfth, and fifth within the aa index between 1868–2010. Among them, the geomagnetic storm on 1941 March 1 was so intense that three of the four Dst station magnetograms went off scale. Herein, we reconstruct its time series and measure the storm intensity with an alternative Dst estimate (Dst*). The source solar eruption at 09:29–09:38 GMT on February 28 was located at RGO AR 13814 and its significant intensity is confirmed by large magnetic crochets of |35| nT measured at Abinger. This solar eruption most likely released a fast interplanetary coronal mass ejection with estimated speed 2260 km s−1. After its impact at 03:57–03:59 GMT on March 1, an extreme magnetic storm was recorded worldwide. Comparative analyses on the contemporary magnetograms show the storm peak intensity of minimum Dst* ≤ −464 nT at 16 GMT, comparable to the most and the second most extreme magnetic storms within the standard Dst index since 1957. This storm triggered significant low-latitude aurorae in the East Asian sector and their equatorward boundary has been reconstructed as 38°.5 in invariant latitude. This result agrees with British magnetograms, which indicate an auroral oval moving above Abinger at 53°.0 in magnetic latitude. The storm amplitude was even more enhanced in equatorial stations and consequently casts caveats on their usage for measurements of the storm intensity in Dst estimates. **February 28-March 1 1941**

Extreme Space Weather Events Recorded in History

Hisashi **Hayakawa**, Yusuke Ebihara

Solar-Terrestrial Environment Prediction, **2020**

https://arxiv.org/ftp/arxiv/papers/2003/2003.06020.pdf **written in Japanese**

This section shows an overview of a recent development of the studies on great space weather events in history. Its discussion starts from the Carrington event and compare its intensity with the extreme storms within the coverage of the regular magnetic measurements. Extending its analyses back beyond their onset, this section shows several case studies of extreme storms with sunspot records in the telescopic observations and candidate auroral records in historical records. Before the onset of telescopic observations, this section shows the chronological coverages of the records of unaided-eye sunspot and candidate aurorae and several case studies on their basis.

See Project for Solar-Terrestrial Environment Prediction (PSTEP) https://www.pstep.jp/?lang=en

Temporal and Spatial Evolutions of a Large Sunspot Group and Great Auroral Storms around the Carrington Event in 1859

Hisashi **Hayakawa**, Yusuke Ebihara, David M. Willis, Shin Toriumi, Tomoya Iju, Kentaro Hattori, Matthew N. Wild, Denny M. Oliveira, Ilaria Ermolli, José R. Ribeiro, Ana P. Correia, Ana I. Ribeiro, Delores J. Knipp

Space Weather **2019**

https://arxiv.org/ftp/arxiv/papers/1908/1908.10326.pdf

The Carrington event is considered to be one of the most extreme space weather events in observational history within a series of magnetic storms caused by extreme interplanetary coronal mass ejections (ICMEs) from a large and complex active region (AR) emerged on the solar disk. In this article, we study the temporal and spatial evolutions of the source sunspot active region and visual aurorae, and compare this storm with other extreme space weather events on the basis of their spatial evolution. Sunspot drawings by Schwabe, Secchi, and Carrington describe the position and morphology of the source AR at that time. Visual auroral reports from the Russian Empire, Iberia, Ireland, Oceania, and Japan fill the spatial gap of auroral visibility and revise the time series of auroral visibility in mid to low magnetic latitudes (MLATs). The reconstructed time series is compared with magnetic measurements and shows the correspondence between low to mid latitude aurorae and the phase of magnetic storms. The spatial evolution of the auroral oval is compared with those of other extreme space weather events in 1872, 1909, 1921, and 1989 as well as their storm intensity, and contextualizes the Carrington event, as one of the most extreme space weather events, but likely not unique. **28/29 Aug 1859, 1/2 Sept 1859, 4 Feb 1872, 25 Sept 1909, 14/15 May 1921, 13/14 March 1989**

The extreme space weather event in September 1909

Hisashi **Hayakawa** Yusuke Ebihara Edward W Cliver Kentaro Hattori Shin ToriumiJeffrey J Love Norio Umemura Kosuke Namekata Takahito Sakaue Takuya Takahashi... Show more

MNRAS, Volume 484, Issue 3, 11 April **2019**, Pages 4083–4099,

https://doi.org/10.1093/mnras/sty3196

http://sci-hub.tw/10.1093/mnras/sty3196

We evaluate worldwide low-latitude auroral activity associated with the great magnetic storm of September 1909 for which a minimum Dst value of −595 nT has recently been determined. From auroral observations, we calculate that the equatorward boundary of the auroral oval in the 1909 event was in the range from 31°–35° invariant latitude (assuming auroral height of 400 km) to 37°–38° (800 km). These locations compare with satellite-based observations of precipitating auroral electrons down to 40° magnetic latitude for the **March 1989** storm with its comparable minimum Dst value of −589 nT. According to Japanese auroral records, bluish colour started to appear first, followed by reddish colour. The colour change can be attributed to the transition from sunlit aurora to the usual low-latitude reddish aurora. Telegraph communications were disrupted at mid/low latitudes, coincidently with the storm main phase and the early recovery phase. The telegraphic disturbances were caused by geomagnetically induced currents associated with the storm-time ring current and substorm current wedge. From the calculated CME energy ─ based on the 24.75 hr separation between the flare-associated magnetic crochet and the geomagnetic storm sudden commencement and interplanetary conditions inferred from geomagnetic data ─ and consideration of the ~−40 nT crochet amplitude, we estimated that the soft X-ray class of the **24 September 1909** flare was ≥X10. As is the case for other extreme storms, strong/sharp excursions in the horizontal component of the magnetic field observed at low-latitude magnetic stations were coincident with the observation of low-latitude aurora.

Low-Latitude Aurorae during the Extreme Space Weather Events in 1859

Hisashi **Hayakawa**, Yusuke Ebihara, David P. Hand, Satoshi Hayakawa, Sandeep Kumar, Shyamoli Mukherjee, B.Veenadhari

ApJ **2018**

https://arxiv.org/ftp/arxiv/papers/1811/1811.02786.pdf

sci-hub.tw/10.3847/1538-4357/aae47c

The Carrington storm (**September 1/2, 1859**) is one of the largest magnetic storms ever observed and it has caused global auroral displays in low-latitude areas, together with a series of multiple magnetic storms during August 28 and September 4, 1859. In this study, we revisit contemporary auroral observation records to extract information on their elevation angle, color, and direction to investigate this stormy interval in detail. We first examine their equatorward boundary of "auroral emission with multiple colors" based on descriptions of elevation angle and color. We find that their locations were 36.5 deg ILAT on August 28/29 and 32.7 deg ILAT on September 1/2, suggesting that trapped electrons moved to, at least, L~1.55 and L~1.41, respectively. The equatorward boundary of "purely red emission" was likely located at 30.8 deg ILAT on September 1/2. If "purely red emission" was a stable auroral red arc, it would suggest that trapped protons moved to, at least, L~1.36. This reconstruction with observed auroral emission regions provides conservative estimations of magnetic storm intensities. We compare the auroral records with magnetic observations. We confirm that multiple magnetic storms occurred during this stormy interval, and that the equatorward expansion of the auroral oval is consistent with the timing of magnetic disturbances. It is possible that the August 28/29 interplanetary coronal mass ejections (ICMEs) cleared out the interplanetary medium, making the ICMEs for the Carrington storm on September 1/2 more geoeffective.

A Great Space Weather Event in February 1730

Hisashi **Hayakawa**, Yusuke Ebihara, José M. Vaquero, Kentaro Hattori, Víctor M. S. Carrasco, María de la Cruz Gallego, Satoshi Hayakawa, Yoshikazu Watanabe, Kiyomi Iwahashi, Harufumi Tamazawa, Akito D. Kawamura, Hiroaki Isobe

A&A 616, A177 **2018**

https://arxiv.org/ftp/arxiv/papers/1807/1807.06496.pdf

Aims. Historical records provide evidence of extreme magnetic storms with equatorward auroral extensions before the epoch of systematic magnetic observations. One significant magnetic storm occurred on February 15, 1730. We scale this magnetic storm with auroral extension and contextualise it based on contemporary solar activity.
Methods. We examined historical records in East Asia and computed the magnetic latitude (MLAT) of observational sites to scale magnetic storms. We also compared them with auroral records in Southern Europe. We examined contemporary sunspot observations to reconstruct detailed solar activity between 1729 and 1731.
Results. We show 29 auroral records in East Asian historical documents and 37 sunspot observations.
Conclusions. These records show that the auroral displays were visible at least down to 25.8{\deg} MLAT throughout East Asia. In comparison with contemporary European records, we show that the boundary of the auroral display closest to the equator surpassed 45.1{\deg} MLAT and possibly came down to 31.5{\deg} MLAT in its maximum phase, with considerable brightness. Contemporary sunspot records show an active phase in the first half of 1730 during the declining phase of the solar cycle. This magnetic storm was at least as intense as the magnetic storm in 1989, but less intense than the Carrington event.

The Great Space Weather Event during February 1872 Recorded in East Asia

Hisashi **Hayakawa**, Yusuke Ebihara, David M. Willis, Kentaro Hattori, Alessandra S. Giunta, Matthew N. Wild, Satoshi Hayakawa, Shin Toriumi, Yasuyuki Mitsuma, Lee T. Macdonald, Kazunari Shibata, Sam M. Silverman

ApJ 862 15 **2018**

https://arxiv.org/ftp/arxiv/papers/1807/1807.05186.pdf

The study of historical great geomagnetic storms is crucial for assessing the possible risks to the technological infrastructure of a modern society, caused by extreme space-weather events. The normal benchmark has been the great geomagnetic storm of September 1859, the so-called "Carrington Event". However, there are numerous records of another great geomagnetic storm in February 1872. This storm, about 12 years after the Carrington Event, resulted in comparable magnetic disturbances and auroral displays over large areas of the Earth. We have revisited this great geomagnetic storm in terms of the auroral and sunspot records in the historical documents from East Asia. In particular, we have surveyed the auroral records from East Asia and estimated the equatorward boundary of the auroral oval to be near 24.3 deg invariant latitude (ILAT), on the basis that the aurora was seen near the zenith at Shanghai (20 deg magnetic latitude, MLAT). These results confirm that this geomagnetic storm of February 1872 was as extreme as the Carrington Event, at least in terms of the equatorward motion of the auroral oval. Indeed, our results support the interpretation of the simultaneous auroral observations made at Bombay (10 deg MLAT). The East Asian auroral records have indicated extreme brightness, suggesting unusual precipitation of high-intensity, low-energy electrons during this geomagnetic storm. We have compared the duration of the East Asian auroral displays with magnetic observations in Bombay and found that the auroral displays occurred in the initial phase, main phase, and early recovery phase of the magnetic storm.

Long-Lasting Extreme Magnetic Storm Activities in 1770 Found in Historical Documents

Hisashi **Hayakawa**, Kiyomi Iwahashi, Yusuke Ebihara, Harufumi Tamazawa, Kazunari Shibata, Delores J. Knipp, Akito Davis Kawamura, Kentaro Hattori,Kumiko Mase, Ichiro Nakanishi, Hiroaki Isobe

ApJL **850** L31 **2017**

https://arxiv.org/ftp/arxiv/papers/1711/1711.00690.pdf

Dim red aurora at low magnetic latitudes is a visual and recognized manifestation of geomagnetic storms. The great low-latitude auroral displays seen throughout East Asia on **16-18 September 1770** are considered to manifest one of the greatest storms. Recently found 111 historical documents in East Asia attest that these low-latitude auroral displays were succeeding for almost 9 nights during 10-19 September 1770 in the lowest magnetic latitude areas (< 30{\deg}). This suggests that the duration of the great magnetic storm is much longer than usual. Sunspot drawings from 1770 reveals the fact that sunspots area was twice as large as those observed in another great storm of 1859, which substantiates this unusual storm activities in 1770. These spots likely ejected several huge, sequential magnetic structures in short duration into interplanetary space, resulting in spectacular world-wide aurorae in mid-September 1770. These findings provide new insights about the history, duration, and effects of extreme magnetic storms that may be valuable for those who need to mitigate against extreme events.

Solar Flare Effects on the Earth's Lower Ionosphere

Laura A. **Hayes**, Oscar S.D. O'Hara, Sophie A. Murray, Peter T. Gallagher

Solar Phys. **296**, Article number: 157 **2021**

https://arxiv.org/pdf/2109.06558.pdf

https://link.springer.com/content/pdf/10.1007/s11207-021-01898-y.pdf

https://doi.org/10.1007/s11207-021-01898-y

Solar flares significantly impact the conditions of the Earth's ionosphere. In particular, the sudden increase in X-ray flux during a flare penetrates down to the lowest-lying D-region and dominates ionization at these altitudes (60-100 km). Measurements of very low frequency (VLF: 3-30kHz) radio waves that reflect at D-region altitudes provide a unique remote-sensing probe to investigate the D-region response to solar flare emissions. Here, using a combination of VLF amplitude measurements at 24kHz together with X-ray observations from the Geostationary Operational Environment Satellite (GOES) X-ray sensor, we present a large-scale statistical study of 334 solar flare events and their impacts on the D-region over the past solar cycle. Focusing on both GOES broadband X-ray channels, we investigate how the flare peak fluxes and position on the solar disk dictate an ionospheric response and extend this to investigate the characteristic time delay between incident X-ray flux and the D-region response. We show that the VLF amplitude linearly correlates with both the 1-8 A and 0.5-4 A channels, with correlation coefficients of 0.80 and 0.79, respectively. Unlike higher altitude ionospheric regions for which the location of the flare on the solar disk affects the ionospheric response, we find that the D-region response to solar flares does not depend on the flare location. By comparing the time delays between the peak X-ray fluxes in both GOES channels and VLF amplitudes, we find that there is an important difference between the D-region response and the X-ray spectral band. We also demonstrate for several flare events that show a negative time delay, the peak VLF amplitude matches with the impulsive 25-50 keV hard X-ray fluxes measured by the Ramaty High Energy Solar Spectroscopic Imager (RHESSI). **2012-11-20, 2 Oct 2015**

Impact of thermospheric mass density on the orbit prediction of LEO satellites

Changyong **He**, Yang Yang, Brett Carter, Kefei Zhang, Andong Hu, Wang Li, Florent Deleflie, Robert Norman, Suqin Wu

Space Weather **2019**

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019SW002336

Many thermospheric mass density (TMD) variations have been recognized in observations and physical simulations, however, their impact on the low-Earth-orbit (LEO) satellites has not been fully evaluated. The present study investigates the quantitative impact of periodic spatiotemporal TMD variations modulated by the empirical DTM2013 model. Also considered are two small-scale variations, i.e., the equatorial mass anomaly (EMA) and the midnight density maximum (MDM), which are reproduced by the Thermosphere-Ionosphere-Electrodynamics General Circulation Model. This investigation is performed through a one-day orbit prediction (OP) simulation for a 400-km circular orbit. The results show that the impact of TMD variations during solar maximum is one order of magnitude larger than that during solar minimum. The dominant impact has been found in the along-track direction. Semi-annual and semi-diurnal variations in TMD exert the most significant impact on OP among the intra-annual and intra-diurnal variations, respectively. The zero mean periodic variations in TMD may not significantly affect the predicted orbit but increase the orbital uncertainty if their periods are shorter than the time span of OP. Additionally, the EMA creates a mean orbit difference of 50 m (5 m) with a standard deviation of 30 m (3 m) in one-day OP during high (low) solar activity. The MDM exhibits a stronger impact in the order of 150 ± 30 m and 15 ± 6 m during solar maximum and solar minimum, respectively. This study makes clear that careful selection of TMD variations is of great importance to balance the trade-off between efficiency and accuracy in OP problems.

Space Weather Societal Impacts Workshop and Seminar at the 55th Meeting of the United Nations Committee on the Peaceful Uses of Outer Space

Head, James; Haubold, Hans

Space Weather, Vol. 10, No. 11, S11007, **2012**

http://dx.doi.org/10.1029/2012SW000874

Science and policy experts discuss phenomena and international efforts to address hazards

Cost-Loss Analysis of Ensemble Solar Wind Forecasting: Space Weather Use of Terrestrial Weather Tools

E. M. **Henley**, E. C. D. Pope

Space Weather December **2017** Vol: 15, Pages: 1562–1566

http://onlinelibrary.wiley.com/doi/10.1002/2017SW001758/epdf

Space Weather Quarterly Vol. 15, Issue 1, **2018**

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/swq.17

This commentary concerns recent work on solar wind forecasting by Owens and Riley (2017, https://doi.org/10.1002/2017SW001679). The approach taken makes effective use of tools commonly used in terrestrial weather—notably, via use of a simple model—generation of an “ensemble” forecast, and application of a “cost-loss” analysis to the resulting probabilistic information, to explore the benefit of this forecast to users with different risk appetites. This commentary aims to highlight these useful techniques to the wider space weather audience and to briefly discuss the general context of application of terrestrial weather approaches to space weather.

Forecasting F10.7 with solar magnetic flux transport modeling

Henney, C. J.; Toussaint, W. A.; White, S. M.; Arge, C. N.

Space Weather, Vol. 10, No. 2, S02011, **2012**

http://dx.doi.org/10.1029/2011SW000748

http://onlinelibrary.wiley.com/doi/10.1029/2011SW000748/pdf

A new method is presented here to forecast the solar 10.7 cm (2.8 GHz) radio flux, abbreviated F10.7, utilizing advanced predictions of the global solar magnetic field generated by a flux transport model. Using indices derived from the absolute value of the solar magnetic field, we find good correlation between the observed photospheric magnetic activity and the observed F10.7 values. Comparing magnetogram data observed within 6 hours of the F10.7 measurements during the years 1993 through 2010, the Spearman correlation coefficient, rs, for an empirical model of F10.7 is found to be 0.98. In addition, we find little change in the empirical model coefficients and correlations between the first and second 9 year intervals of the 18 year period investigated. By evolving solar magnetic synoptic maps forward 1–7 days, this new method provides a realistic estimation of the Earth-side solar magnetic field distribution used to forecast F10.7. Spearman correlation values of approximately 0.97, 0.95, and 0.93 are found for 1 day, 3 day, and 7 day forecasts, respectively. The method presented here can be expanded to forecast other space weather parameters, e.g., total solar irradiance and extreme ultraviolet flux. In addition, near-term improvements to the F10.7 forecasting method, e.g., including far-side magnetic data with solar magnetic flux transport, are discussed.

A New Model Suite to Determine the Influence of Cosmic Rays on (Exo)planetary Atmospheric Biosignatures -- Validation based on Modern Earth

Konstantin **Herbst**, John Lee Grenfell, Miriam Sinnhuber, Heike Rauer, Bernd Heber, Saša Banjac, Markus Scheucher, Vanessa Schmidt, Stefanie Gebauer, Ralph Lehmann, Franz Schreier

A&A **2019**

https://arxiv.org/pdf/1909.11632.pdf

The first opportunity to detect indications for life outside the Solar System may be provided already within the next decade with upcoming missions such as the James Webb Space Telescope (JWST), the European Extremely Large Telescope (E-ELT) and/or the Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL) mission, searching for atmospheric biosignatures on planets in the habitable zone of cool K- and M-stars. Nevertheless, their harsh stellar radiation and particle environment could lead to photochemical loss of atmospheric biosignatures. We aim to study the influence of cosmic rays on exoplanetary atmospheric biosignatures and the radiation environment considering feedbacks between energetic particle precipitation, climate, atmospheric ionization, neutral and ion chemistry, and secondary particle generation. We describe newly-combined state-of-the-art modeling tools to study the impact of the radiation and particle environment on atmospheric particle interaction, the influence on the atmospheric chemistry, and the climate-chemistry coupling in a self-consistent model suite. To this end, models like the Atmospheric Radiation Interaction Simulator (AtRIS), the Exoplanetary Terrestrial Ion Chemistry model (ExoTIC), and the updated coupled climate-chemistry model are combined. Amongst others, we model the atmospheric response during quiescent solar periods and during a strong solar energetic particle event as well as the scenario-dependent terrestrial transit spectra, as seen by the NIR-Spec infrared spectrometer onboard the JWST. We find that the comparatively weak solar event drastically increases the spectral signal of HNO3, while significantly suppressing the spectral feature of ozone. Because of the slow recovery after such events, the latter indicates that ozone might not be a good biomarker for planets orbiting stars with high flaring rates.

Real-time detection, location and measurement of geoeffective stellar flares from Global Navigation Satellite System data: new technique and case studies

Manuel **Hernández-Pajares** & David Moreno-Borràs
Space Weather 18, e2020SW002441 **2020**
sci-hub.si/10.1029/2020SW002441
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020SW002441

An alternative approach to detect solar flares and quantify the associated Extreme UltraViolet (EUV) solar flux rate was introduced in this journal by the authors: GSFLAI was founded on the dependence of the sudden electron content increase of the Earth ionosphere vs. the angle regarding the flare source, the sun, given by a simple but accurate first-principle based model. Such overionization is directly measured from the dual-frequency phase measurements gathered from hundreds of worldwide permanent Global Navigation Satellite Systems receivers (GNSS, like the Global Positioning System GPS), working many of them in real-time.
In this work we generalize GSFLAI for the very challenging scenario of stellar superflares, with a much weaker expected geoeffectiveness on the Earth ionosphere, making difficult to distinguish its potential footprint regarding to conventional ionospheric variability sources. Indeed, we will show that, unlike GSFLAI for solar-flares, the new algorithm presented here (BGEES) is able to detect EUV flares without the previous knowledge of the position of the source, which is also simultaneosly estimated, providing an additional quality check of the detection. It will be firstly assessed with several case studies of solar flares of different intensities, analyzed previously with GSFLAI. Finally, by focusing on the night hemisphere to avoid the Sun's larger effect on the ionosphere, the detection and location with BGEES of two recent stellar superflares, Proxima Centauri (**18th March 2016**, 08:32UT) and NGTS J121939.5-355557 (**1st February 2016**, 04:00UT), are presented, strongly suggesting the extension and applicability of the new technique, either in real-time.

Solar Origins of Space Weather and Space Climate: Preface

I. Gonzalez **Hernandez** · R. Komm · A. Pevtsov · J.W. Leibacher
Solar Phys (**2014**) 289:437–439

As the impact of space weather and climate on daily life is becoming more important, it is timely to discuss the latest research on the solar origin of these phenomena. Recent advances in helioseismology have demonstrated that keys for understanding many aspects of solar activity from flare and CME eruptions to cyclic variations may lie with the subphotospheric plasma dynamics. On the other hand, the advent of synoptic vector magnetic-field measurements opens up a new path to a better understanding of magnetic topology of space-weather source regions on the Sun, *e.g.* active regions, flares, chromospheric filaments, and CMEs. Furthermore, the space-weather research is rapidly maturing, and is now becoming capable of producing stable space-weather forecasts. Despite this recent progress, many questions remain to be answered, including the future directions for the research and applied components of space weather, the role of ground-based and space-borne instrumentation and networks, and the ways for transitioning the results of research into the operational forecast. This topical issue is based on the presentations given at the 26th National Solar Observatory (NSO) Summer Workshop *Solar Origins of Space Weather and Space Climate* held at the National Solar Observatory/Sacramento Peak, New Mexico, USA from 30 April to 4 May 2012.

Comparing Automatic CME Detections in Multiple LASCO and SECCHI Catalogs

Phillip **Hess**1 and Robin C. Colaninno
2017 ApJ 836 134
http://iopscience.iop.org.sci-hub.cc/0004-637X/836/1/134/

With the creation of numerous automatic detection algorithms, a number of different catalogs of coronal mass ejections (CMEs) spanning the entirety of the Solar and Heliospheric Observatory (SOHO) Large Angle Spectrometric Coronagraph (LASCO) mission have been created. Some of these catalogs have been further expanded for use on data from the Solar Terrestrial Earth Observatory (STEREO) Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) as well. We compare the results from different automatic detection catalogs (Solar Eruption Event Detection System (SEEDS), Computer Aided CME Tracking (CACTus), and Coronal Image Processing (CORIMP)) to ensure the consistency of detections in each. Over the entire span of the LASCO catalogs, the automatic catalogs are well correlated with one another, to a level greater than 0.88. Focusing on just periods of higher activity, these correlations remain above 0.7. We establish the difficulty in comparing detections over the course of LASCO observations due to the change in the instrument image cadence in 2010. Without adjusting catalogs for the cadence, CME detection rates show a large spike in cycle 24, despite a notable drop in other indices of solar activity. The output from SEEDS, using a consistent image cadence, shows that the CME rate has not significantly changed relative to sunspot number in cycle 24. These data, and mass calculations from CORIMP, lead us to conclude that any apparent increase in CME rate is a result of the change in cadence. We study detection characteristics of CMEs, discussing potential physical changes in events between cycles 23 and 24. We establish that, for detected CMEs, physical parameters can also be sensitive to the cadence.

Solar Magnetic Feature Detection and Tracking for Space Weather Monitoring

Paul A. **Higgins**, Peter T. Gallagher, R.T. James McAteer, D. Shaun Bloomfield
E-print, July 2010,
Advances in Space Research
Volume 47, Issue 12, 15 June **2011**, Pages 2105-2117
http://arxiv.org/pdf/1006.5898v1.pdf
We present an automated system for detecting, tracking, and cataloging emerging active regions throughout their evolution and decay using SOHO Michelson Doppler Interferometer (MDI) magnetograms. ***The SolarMonitor Active Region Tracking (SMART)*** algorithm relies on consecutive image differencing to remove both quiet-Sun and transient magnetic features, and region-growing techniques to group flux concentrations into classifiable features. We determine magnetic properties such as region size, total flux, flux imbalance, flux emergence rate, Schrijver's R-value, R* (a modified version of R), and Falconer's measurement of non-potentiality. A persistence algorithm is used to associate developed active regions with emerging flux regions in previous measurements, and to track regions beyond the limb through multiple solar rotations. We find that the total number and area of magnetic regions on disk vary with the sunspot cycle. While sunspot numbers are a proxy to the solar magnetic field, SMART offers a direct diagnostic of the surface magnetic field and its variation over timescale of hours to years. SMART will form the basis of the active region extraction and tracking algorithm for the Heliophysics Integrated Observatory (HELIO).

Space Weather Workshop: A Catalyst for Partnerships

Hildner, Ernest; Singer, Howard; Onsager, Terrance
Space Weather, Vol. 9, No. 3, S03006, **2011**
From its inception in 1999 as a meeting bringing together space weather researchers, service users, and service providers, NOAA's Space Weather Workshop (SWW) has been a valued annual multiday meeting in which participants share knowledge to advance the development and use of improved space weather services. SWW has been the primary U.S. meeting that brings together government and commercial space weather service providers, service users, and researchers with the goal of focusing national attention on commercial and government needs for space weather information. The meeting gathers much of the space weather community to exhibit and share information about the current status and evolution of space weather activities. With an emphasis on societal needs, SWW has been a catalyst for partnerships and a forum for planning and discussing the valuable programs, policies, and activities that have advanced society's space weather capabilities.
See http://www.swpc.noaa.gov/sww/

The Global Oscillation Network Group Facility—An Example of Research to Operations in Space Weather

Frank **Hill**
Space Weather Volume16, Issue10 October **2018** Pages 1488-1497
http://sci-hub.tw/10.1029/2018SW002001
The Global Oscillation Network Group (GONG) is a system of ground-based solar observing stations distributed geographically so that the Sun is visible nearly continuously at all times. Originally developed to provide data for research into the solar interior via helioseismology, GONG is now also providing data for operational space weather forecasting as a cost-effective and reliable alternative to space missions. The data comprise full-disk magnetograms, H-α intensity images, and helioseismic maps of activity on the solar far side. These data are provided in near real

time to the NOAA Space Weather Prediction Center, the US Air Force, and NASA. GONG is a successful example of transitioning a research facility funded by the NSF into an operational asset.

Workshop Report: A New Synoptic Solar Observing Network

Frank **Hill**1, Michael J. Thompson2, Markus Roth
Space Weather, Volume 11, Issue 7, pages 392–393, July **2013**
Ground-based networks are valuable space weather assets
Multi-wavelength observations provide solar height information
Multi-instrument platform provides flexibility

Investigating the Effects of Cosmic Rays on Space Electronics

Stefan K. **Höeffgen**, Stefan Metzger* and Michael Steffens
Front. Phys., **2020**
https://doi.org/10.3389/fphy.2020.00318
https://www.frontiersin.org/articles/10.3389/fphy.2020.00318/full

The radiation environment in space has severe adverse effects on electronic systems. To evaluate radiation sensitivity, electronics are tested on earth with different types of irradiation sources. Cosmic rays (CR) are the most difficult to simulate on earth, because CR can have energies up to 1020 eV, with a flux maximum of around 1 GeV/n. However, only particles with energies up to several GeV/nucleon are relevant for radiation effect testing of space electronics due to the negligible fluxes beyond. Traditionally single-event effects of these particles were simulated with heavy ions having energies of only a few MeV/n because for "large" devices only the energy loss, often referred to as linear energy transfer (LET), had to be matched. Heavy ions of such high energies can produce secondary particles through nuclear interactions which can induce additional ionization that leads to adverse effects. The need to investigate these effects has grown since electronic devices now incorporate heavier elements (e.g., Cu, W) close to sensitive elements which can have significantly larger nuclear cross sections than in the 1 to 10 MeV/n energy regime. At the moment there is a large trend in the space community to increasingly use commercial off-the-shelf (COTS) electronic devices. One of the reasons is that many challenging space applications can only be met with COTS devices because there are simply no space-qualified devices [often referred to as High Reliability (HiRel)] available with the necessary performance. Another trend in the evolution of Si-based microelectronic integrated circuits is to create 3-dimensional (3D) structures. There are already commercially available 3D NAND-Flash devices [i.e., a type of non-volatile computer memory that uses floating-gate transistors that resembles a NAND (NOT-AND) gate] with several tens of active layers stacked on top of each other. These structures cannot be tested with low energy ions, due to the large depths of the sensitive volumes alone. For radiation tests ion beams are needed that provide constant LET over the whole stack (> 128 layers). In addition, e.g., in systems in a package, one finds several dies stacked on top of each in a single package. To investigate the aforementioned device types, the beam has to be able to penetrate through all the dies.

Space Weather and its Effects on Satellites

Richard B. **Horne**
LECTURE at 3rd URSI Atlantic Radio Science Meeting 2022
Abstract https://www.atrasc.com/content/HorneAbstract.pdf

The Satellite Risk Prediction and Radiation Forecast System (SaRIF)

Richard B. **Horne**, Sarah A. Glauert, Peter Kirsch, Daniel Heynderickx, Suzy Bingham, Peter Thorn, Babara-Ann Curran, David Pitchford, Ewan Haggarty, David Wade, Ralf Keil
Space Weather e2021SW002823 **2021**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021SW002823
https://doi.org/10.1029/2021SW002823

With new satellite constellations being launched into low Earth orbit, the growing use of medium Earth orbit for radio-navigation and timing signals, slot region orbits for telecommunications and the introduction of electric propulsion to reach geostationary orbit, there is a growing need to develop services to protect satellites from space weather. Here we highlight two recent events in relation to satellite operations. We summarise ten user needs that arose out of meetings with satellite operators, designers, underwriters and space agency staff. We present the satellite risk prediction and radiation forecast (SaRIF) system which is designed to meet most of these needs. The system uses real-time data as input to the BAS radiation belt model (BAS-RBM) to solve the Fokker Planck equation and provides a forecast of the electron flux throughout the outer radiation belt with 1-hour resolution up to 24 hours ahead. The electron flux is used to calculate charging currents, and is combined with GOES near real time proton fluxes to calculate dose rate and total ionizing dose behind set levels of shielding for satellites in Medium Earth orbit, Geostationary orbit and slot region orbits. The results are compared against design standards and presented as risk indicators to forecast the risk of damage. The system works automatically and is updated every hour. We also present data and a best reconstruction of the radiation environment which are held in a searchable archive for satellite anomaly resolution. The SaRIF system is available via the European Space Agency space weather web portal.

Realistic Worst Case for a Severe Space Weather Event Driven by a Fast Solar Wind Stream

Richard B. **Horne** , Mark W. Phillips, Sarah A. Glauert, Nigel P. Meredith, Alex D. P. Hands, Keith A. Ryden, Wen Li

Space Weather Volume16, Issue9 September **2018** Pages 1202-1215

https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2018SW001948

Satellite charging is one of the most important risks for satellites on orbit. Satellite charging can lead to an electrostatic discharge resulting in component damage, phantom commands, and loss of service and in exceptional cases total satellite loss. Here we construct a realistic worst case for a fast solar wind stream event lasting 5 days or more and use a physical model to calculate the maximum electron flux greater than 2 MeV for geostationary orbit. We find that the flux tends toward a value of 106 cm−2·s−1·sr−1 after 5 days and remains high for another 5 days. The resulting flux is comparable to a 1 in 150-year event found from an independent statistical analysis of electron data. Approximately 2.5 mm of Al shielding would be required to reduce the internal charging current to below the National Aeronautics and Space Administration-recommended guidelines, much more than is currently used. Thus, we would expect many satellites to report electrostatic discharge anomalies during such an event with a strong likelihood of service outage and total satellite loss. We conclude that satellites at geostationary orbit are more likely to be at risk from fast solar wind stream event than a Carrington-type storm.

Forecasting the Radiation Belts in Europe

Horne, R. B.

Space Weather, Vol. 10, No. 8, S08006, **2012**

http://dx.doi.org/10.1029/2012SW000808

The SPACECAST project will help protect high-technology systems susceptible to space weather
Weather forecasting has expanded to space weather. As of 1 March 2012, satellite operators and the general public will be able to obtain forecasts of the Earth's radiation belts, thanks to the SPACECAST project. The opening of the first European system to forecast Earth's radiation belts, part of the SPACECAST project, is funded by the European Union Framework 7 Programme and provides a forecast of high-energy electrons up to 3 hours in advance (updated every hour), as well as a risk index for the satellite operations and service industry.

See http://fp7-spacecast.eu/index.php?page=project_description

Space Weather and Coronal Mass Ejections **Book**

Timothy A. **Howard**

Springer, **2013**

http://books.google.ru/books?id=ihO4BAAAQBAJ&pg=PA97&lpg=PA97&dq=DeForest,+C.+E.&source=bl&ots=XIvsgYLfFB&sig=525J_9PFZBGda9BsysLsvRRQh34&hl=ru&sa=X&ei=HxlfVOr7HoG6PdDNgegL&ved=0CC4Q6AEwBQ#v=onepage&q=DeForest%2C%20C.%20E.&f=false

25 March 2008, 12-17 Dec 2008, 2010-04-03,

Application of a new phenomenological coronal mass ejection model to space weather forecasting,

Howard, T. A., and S. J. Tappin

Space Weather, 8, S07004, doi:10.1029/2009SW000531 (**2010**).

http://www.boulder.swri.edu/~howard/Papers/2010_TH_SPx.pdf - **File**

Recent work by the authors has produced a new phenomenological model for coronal mass ejections (CMEs). This model, called the Tappin-Howard (TH) Model, takes advantage of the breakdown of geometrical linearity when CMEs are observed by white-light imagers at large distances from the Sun. The model extracts 3-D structure and kinematic information on the CME using heliospheric image data. This can estimate arrival times of the CME at 1 AU and impact likelihood with the Earth. Hence the model can be used for space weather forecasting. We present a preliminary evaluation of this potential with three mock trial forecasts performed using the TH Model. These are already-studied events from 2003, 2004 and 2007 but we performed the trials assuming that they were observed for the first time. The earliest prediction was made 17 hours before impact and predicted arrival times reached differences within one hour for at least one forecast for all three events. The most accurate predicted arrival time was 15 min from the actual, and all three events reach accuracies of the order of 30 min. Arrival speeds were predicted to be very similar to the bulk plasma speed within the CME near 1 AU for each event, with the largest difference around 300 km/s and the least 40 km/s. The model showed great potential and we aspire to fully validate it for integration with existing tools for space weather forecasting.

Deep Learning Based Solar Flare Forecasting Model. I. Results for Line-of-sight Magnetograms

Xin **Huang**1, Huaning Wang1,2, Long Xu1, Jinfu Liu3, Rong Li4, and Xinghua Dai1
2018 ApJ 856 7
http://iopscience.iop.org/article/10.3847/1538-4357/aaae00/pdf
Solar flares originate from the release of the energy stored in the magnetic field of solar active regions, the triggering mechanism for these flares, however, remains unknown. For this reason, the conventional solar flare forecast is essentially based on the statistic relationship between solar flares and measures extracted from observational data. In the current work, the deep learning method is applied to set up the solar flare forecasting model, in which forecasting patterns can be learned from line-of-sight magnetograms of solar active regions. In order to obtain a large amount of observational data to train the forecasting model and test its performance, a data set is created from line-of-sight magnetogarms of active regions observed by SOHO/MDI and SDO/HMI from 1996 April to 2015 October and corresponding soft X-ray solar flares observed by GOES. The testing results of the forecasting model indicate that (1) the forecasting patterns can be automatically reached with the MDI data and they can also be applied to the HMI data; furthermore, these forecasting patterns are robust to the noise in the observational data; (2) the performance of the deep learning forecasting model is not sensitive to the given forecasting periods (6, 12, 24, or 48 hr); (3) the performance of the proposed forecasting model is comparable to that of the state-of-the-art flare forecasting models, even if the duration of the total magnetograms continuously spans 19.5 years. Case analyses demonstrate that the deep learning based solar flare forecasting model pays attention to areas with the magnetic polarity-inversion line or the strong magnetic field in magnetograms of active regions. **2005 January 15, 2011 February 13,**

Study of the Impact of past extreme Solar Events on the modern air traffic

G. Hubert, S. Aubry
Space Weather e2020SW002665 **2021**
https://doi.org/10.1029/2020SW002665
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020SW002665
The ancient SEP events of AD **774/775** and AD **993/994** were characterized thanks to radionuclide productions stored in environmental archives as ice cores or tree rings. Primary cosmic ray spectra deduced from these cosmogenic isotope data indicate that the impact of these extreme SEP events would have been much more significant than any of the ones observed during the modern era. However, the impact of these should be studied more accurately in the framework of the ambient dose equivalent impacting aircrew and passengers in the air traffic context by considering physical parameters such as time profile or anisotropy properties. In this paper the impact that AD 774/775 and AD 993/994 past extreme SEP events could have had on modern air traffic is discussed. Possible event spectra for these ancient events are derived from the spectra **GLE 5** and **GLE 69**, which have been observed during the modern era and have been widely studied/characterized using measurements. The investigations include the impact of the SEP activity on ambient dose equivalent, including detailed analyses considering route, airplane characteristics (departure, arrival, continent, airplane type), and the time occurrence of the SEP event. Statistical analyses show that additional dose levels can reach values on the order of 70 mSv, which is absolutely significant considering the current air traffic recommendations. The orders of magnitude of the ambient dose equivalent induced during past extreme SEP events raises a number of issues, both for aircrews and for avionics hardware. This paper demonstrates that simulations can be useful for the evaluation of risks in case of extreme SEP events. **23 Feb 1956, 20 Jan 2005**

Differential Magnetometer Measurements of Geomagnetically Induced Currents in a Complex High Voltage Network

J. Hübert , C. D. Beggan , G. S. Richardson , T. Martyn , A. W. P. Thomson
Space Weather Volume18, Issue4 April **2020** e2019SW002421
https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2019SW002421
Space weather poses a hazard to grounded electrical infrastructure such as high voltage (HV) transformers, through the induction of geomagnetically induced currents (GICs). Modeling GICs requires knowledge of the source magnetic field and the Earth's electrical conductivity structure, in order to calculate the geoelectric fields generated during magnetic storms, as well as knowledge of the topology of the HV network. Direct measurement of GICs at the ground neutral in substations is possible with a Hall effect probe, but such data are not widely available. To validate our HV network model, we use the differential magnetometer method (DMM) to measure GICs in the 400 kV grid of Great Britain. We present DMM measurements for the **26 August 2018** storm at a site in eastern

Scotland with up to 20 A recorded. The line GIC correlates well with Hall probe measurements at a local transformer, though they differ in amplitude by an order of magnitude (a maximum of 2 A). We deployed a long-period magnetotelluric (MT) instrument to derive the local impedance tensor which can be used to predict the geoelectric field from the recorded magnetic field. Using the MT-derived electric field estimates, we model GICs within the network, accounting for the difference in magnitude between the DMM-measured line currents and earth currents at the local substation. We find that the measured line and earth GICs match the expected GICs from our network model, confirming that detailed knowledge of the complex network topology and its resistance parameters is essential for accurately computing GICs.

An X9 flare and its huge crochet (SFE)

Hugh **HUDSON**
RHESSI Science Nuggets #472 **2024**
https://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/An_X9_flare_and_its_huge_crochet_(SFE)
2024-10-03

Kristian Birkeland

Hugh **Hudson** and Lyndsay Fletcher
RHESSI Nuggets #350 May **2019** http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Kristian_Birkeland
It is timely to remember the Norwegian pioneers of space research, as we have done here with Kristian Birkeland. His scientific innovations, not really properly noted during his time, gain in weight with the years, and perhaps his geomagnetic current systems and terrella experiments have some signficance for solar phenomena.

Revealing Novel Connections Between Space Weather and the Power Grid: Network Analysis of Ground-Based Magnetometer and Geomagnetically Induced Currents (GIC) Measurements

Joseph **Hughes**, Ryan Mcgranaghan, Adam C. Kellerman, Jacob Bortnik, Robert F. Arrit, Karthik Venkataramani, Charles H. Perry, Jackson McCormick, Chigomezyo M. Ngwira, Morris Cohen
Space Weather e2021SW002727 **2021**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021SW002727
https://doi.org/10.1029/2021SW002727
The growing depth and breadth of data spanning the solar-terrestrial environment requires new ways of representing and analyzing the available information. This paper applies one such new data representation - network analysis - to the study of Geomagnetically Induced Currents (GICs) in electric power lines. This work uses newly-available electric current data collected by power utilities through the the Electric Power Research Institute (EPRI) SUNBURST project and magnetometer data from the Super Magnetometer Initiative. The magnetometer data are analyzed using wavelet analysis. This new analysis method shows deviations to be more likely for equatorial stations close to water, which may be caused by the coast effect. The deviation likelihood is a complex function of latitude and magnetic local time. The GIC data are analyzed using “Quiet Day Curves” (QDCs) which help isolate geomagnetic disturbances. We find that current deviations are more common in the early morning sector, but this trend differs from station to station.
These current and magnetometer data are represented in a network as nodes which are connected when both the current and magnetic measurements have a statistically significant deviation from their baseline behavior. This network is used to study the link between space weather and GICs. To do this, times when a current deviation exists are compared to times when magnetic deviations exist for each magnetometer - current sensor pair. Current deviations are, on average, 1.83 times more likely when there are magnetic deviations. However, some magnetometer deviations are more indicative than others, with the strongest probability multipliers reaching 3.

Solar wind drivers of large geomagnetically induced currents during the solar cycle 23

Huttunen, K. E. J.; Kilpua, S. P.; Pulkkinen, A.; Viljanen, A.; Tanskanen, E.
Space Weather, Vol. 6, No. 10, S10002, **2008**
http://dx.doi.org/10.1029/2007SW000374
Scientists examine the effectiveness of different structures embedded in interplanetary coronal mass ejections in causing the largest geomagnetically induced currents of solar cycle 23.

Using Machine Learning Methods to Forecast If Solar Flares Will Be Associated with CMEs and SEPs

Fadil **Inceoglu**, Jacob H. Jeppesen, Peter Kongstad, Nestor J. Hernandez Marcano, Rune H. Jacobsen, Christoffer Karoff

2018 *ApJ* **861** 128
http://sci-hub.tw/10.3847/1538-4357/aac81e
https://arxiv.org/pdf/1806.07117.pdf
Among the eruptive activity phenomena observed on the Sun, the most technology threatening ones are flares with associated coronal mass ejections (CMEs) and solar energetic particles (SEPs). Flares with associated CMEs and SEPs are produced by magnetohydrodynamical processes in magnetically active regions (ARs) on the Sun. However, these ARs do not only produce flares with associated CMEs and SEPs, they also lead to flares and CMEs, which are not associated with any other event. In an attempt to distinguish flares with associated CMEs and SEPs from flares and CMEs, which are unassociated with any other event, we investigate the performances of two machine learning algorithms. To achieve this objective, we employ support vector machines (SVMs) and multilayer perceptrons (MLPs) using data from the Space Weather Database of Notification, Knowledge, Information (DONKI) of NASA Space Weather Center, {\it the Geostationary Operational Environmental Satellite} ({\it GOES}), and the Space-Weather Heliospheric and Magnetic Imager Active Region Patches (SHARPs). We show that True Skill Statistics (TSS) and Heidke Skill Scores (HSS) calculated for SVMs are slightly better than those from the MLPs. We also show that the forecasting time frame of 96 hours provides the best results in predicting if a flare will be associated with CMEs and SEPs (TSS=0.92±0.09 and HSS=0.92±0.08). Additionally, we obtain the maximum TSS and HSS values of 0.91±0.06 for predicting that a flare will not be associated with CMEs and SEPs for the 36 hour forecast window, while the 108 hour forecast window give the maximum TSS and HSS values for predicting CMEs will not be accompanying any events (TSS=HSS=0.98±0.02).

Improved forecasts of solar wind parameters using the Kalman filter

Innocenti, M. E.; Lapenta, G.; Vrsnak, B.; Crespon, F.; Skandrani, C.; Temmer, M.; Veronig, A.; Bettarini, L.; Markidis, S.; Skender, M.
Space Weather, Vol. 9, No. 10, S10005, **2011**
Data assimilation through Kalman filtering is a powerful statistical tool that allows researchers to combine modeling and observations and thus to increase the degree of knowledge of a given system. The application of this technique to an empirical solar wind forecasting model which enables the forecasting of solar wind parameters from coronal hole observations is here described and discussed. The forecasts for the solar wind proton velocity and temperature and for the magnetic field magnitude with and without data assimilation are validated against Advanced Composition Explorer observations, and it is shown that Kalman filtering can improve the quality of the forecasts and extend the period of applicability of the baseline model. In a subset of cases, some degree of robustness toward solar transient activity not accounted for in the original model is also provided.

Third Space Weather Summit Held for Industry and Government Agencies

Devrie S. **Intriligator**
Space Weather, Vol. 7, No. 12, S12006, **2010**
http://dx.doi.org/10.1029/2009SW000529
The potential for space weather effects has been increasing significantly in recent years. For instance, **in 2008 airlines flew about 8000 transpolar flights**, which experience greater exposure to space weather than nontranspolar flights. This is up **from 368 transpolar flights in 2000**, and the number of such flights is expected to continue to grow. Transpolar flights are just one example of the diverse technologies susceptible to space weather effects identified by the National Research Council's Severe Space Weather Events—Understanding Societal and Economic Impacts: A Workshop Report (2008). To discuss issues related to the increasing need for reliable space weather information, experts from industry and government agencies met at the third summit of the Commercial Space Weather Interest Group (CSWIG) and the National Oceanic and Atmospheric Administration's (NOAA) Space Weather Prediction Center (SWPC), held 30 April 2009 during Space Weather Week (SWW), in Boulder, Colo.

Industry and Government Officials Meet for Space Weather Summit

Intriligator, Devrie S.
Space Weather, Vol. 6, No. 10, S10004
http://dx.doi.org/10.1029/2008SW000430
The second annual summit of the Commercial Space Weather Interest Group and the National Oceanic and Atmospheric Administration's Space Weather Prediction Center was held on 1 May 2008 during Space Weather Workshop, in Boulder, Colo.

Japanese space weather research activities
Ishii, M.
Space Weather, Volume 15, Issue 1, pp. 26-35, **2017**
http://sci-hub.cc/10.1002/2016SW001531
http://onlinelibrary.wiley.com/doi/10.1002/2016SW001531/epdf
In this paper, we present existing and planned Japanese space weather research activities. The program consists of several core elements, including a space weather prediction system using numerical forecasts, a large-scale ground-based observation network, and the cooperative framework "Project for Solar-Terrestrial Environment Prediction (PSTEP)" based on a Grant-in Aid for Scientific Research on Innovative Areas.
See Presentation http://slideplayer.com/slide/10982172/

SOLAR GEOEFFECTIVE PHENOMENA: ACTION ON THE ENVIRONMENT SPACE AND THE POSSIBILITY OF THE FORECAST
V. N. Ishkov
См. Файл 2013breus1.pdf
Возможность прогноза геоэффективных солнечных явлений и их воздействий на околоземное космическое пространство основана на исследованиях связей осуществления вспышечных событий с всплывающими новыми магнитными потоками в солнечной атмосфере, физических характеристик этих потоков и характером их взаимодействия с уже существующими магнитными полями, временным распределением больших солнечных вспышек в пределах активных областей, временным и пространственным распределением выбросов солнечных волокон, законами зарождения, эволюции и распределения корональных дыр. Агентами, вызывающими возмущения ОКП, являются: выбросы коронального вещества как следствие активных процессов во вспышках и выбросах волокон; высокоскоростные потоки солнечной плазмы, следующие за ударной волной от больших солнечных вспышечных событий или истекающих из областей с открытой конфигурацией магнитного поля (КД).
Прогноз начал возмущений в ОКП и их длительности возможен на период от 1 до 5 сут, а корональных дыр — на период одного оборота Солнца (27,3 сут).

Iterative Tomography: A Key to Providing Time- dependent 3-D Reconstructions of the Inner Heliosphere and the Unification of Space Weather Forecasting Techniques
Bernard Jackson1*, Andrew Buffington1, Lucas Cota1, Dusan Odstrcil2, Mario M. Bisi3, Richard Fallows4 and Munetoshi Tokumaru
Front. Astron. Space Sci. **2020**|
doi: 10.3389/fspas.2020.568429
Over several decades UCSD has developed and continually updated a time dependent iterative three-dimensional (3-D) reconstruction technique to provide global heliospheric parameters – density, velocity, and component magnetic fields. For expediency, this has used a kinematic model as a kernel to provide a fit to either interplanetary scintillation (IPS) or Thomson-scattering observations. This technique has been used in near real time over this period, employing Institute for Space-Earth Environmental Research (ISEE), Japan IPS data to predict the propagation of these parameters throughout the inner heliosphere.
We have extended the 3-D reconstruction analysis to include other IPS Stations around the Globe in a Worldwide Interplanetary Scintillation Stations (WIPSS) Network. In addition, we also plan to resurrect the Solar Mass Ejection Imager (SMEI) Thomson-scattering analysis as a basis for 3-D analysis to be used by the latest NASA Small Explorer heliospheric imagers of the Polarimeter to Unify the Corona and Heliosphere (PUNCH) mission, the All Sky Heliospheric Imager (ASHI), and other modern wide-field imagers. Better data require improved Heliospheric modeling that incorporates non-radial transport of heliospheric flows, and shock processes. Looking ahead to this, we have constructed an interface between the 3-D reconstruction tomography and 3-D MHD models, and currently include the ENLIL model as a kernel in the reconstructions to provide this fit. In short, we are now poised to provide all of these innovations in a next step: to include them for planned ground-based and spacecraft instruments, all to be combined into a truly global 3-D heliospheric system which utilizes these aspects in their data and modeling.

The Space Weather Atmosphere Models and Indices (SWAMI) project: Overview and first results
David R. **Jackson**1*, Sean Bruinsma2, Sandra Negrin3, Claudia Stolle4, Chris J. Budd5, Raul Dominguez Gonzalez3, Emily Down1,+, Daniel J. Griffin1, Matthew J. Griffith5, Guram

Kervalishvili4, Daniel Lubián Arenillas3, James Manners1,6, Jürgen Matzka4, Yuri Y. Shprits4,7,8, Ruggero Vasile4 and Irina S. Zhelavskaya4,7
J. Space Weather Space Clim. Volume 10, paper 18, **2020**
https://www.swsc-journal.org/articles/swsc/pdf/2020/01/swsc190071.pdf
Space weather driven atmospheric density variations affect low Earth orbit (LEO) satellites during all phases of their operational lifetime. Rocket launches, re-entry events and space debris are also similarly affected. A better understanding of space weather processes and their impact on atmospheric density is thus critical for satellite operations as well as for safety issues. The Horizon 2020 project Space Weather Atmosphere Model and Indices (SWAMI) project, which started in January 2018, aims to enhance this understanding by:

- Developing improved neutral atmosphere and thermosphere models, and combining these models to produce a new whole atmosphere model.
- Developing new geomagnetic activity indices with higher time cadence to enable better representation of thermospheric variability in the models, and improving the forecast of these indices.

The project stands out by providing an integrated approach to the satellite neutral environment, in which the main space weather drivers are addressed together with model improvement. The outcomes of SWAMI will provide a pathway to improved space weather services as the project will not only address the science issues, but also the transition of models into operational services.
The project aims to develop a unique new whole atmosphere model, by extending and blending the Unified Model (UM), which is the Met Office weather and climate model, and the Drag Temperature Model (DTM), which is a semi-empirical model which covers the 120–1500 km altitude range. A user-focused operational tool for satellite applications shall be developed based on this. In addition, improved geomagnetic indices shall be developed and shall be used in the UM and DTM for enhanced nowcast and forecast capability.
In this paper, we report on progress with SWAMI to date. The UM has been extended from its original upper boundary of 85 km to run stably and accurately with a 135 km lid. Developments to the UM radiation scheme to enable accurate performance in the mesosphere and lower thermosphere are described. These include addition of non-local thermodynamic equilibrium effects and extension to include the far ultraviolet and extreme ultraviolet. DTM has been re-developed using a more accurate neutral density observation database than has been used in the past. In addition, we describe an algorithm to develop a new version of DTM driven by geomagnetic indices with a 60 minute cadence (denoted Hp60) rather than 3-hourly Kp indices (and corresponding ap indices). The development of the Hp60 index, and the Hp30 and Hp90 indices, which are similar to Hp60 but with 30 minute and 90 minute cadences, respectively, is described, as is the development and testing of neural network and other machine learning methods applied to the forecast of geomagnetic indices.

Future Directions for Whole Atmosphere Modeling: Developments in the Context of Space Weather **Review**

David R. **Jackson**, Tim J. Fuller-Rowell, Dan J. Griffin, Matthew J. Griffith, Christopher W. Kelly, Daniel R. Marsh, Maria-Theresia Walach
Space Weather Volume17, Issue9 September **2019** Pages 1342-1350
sci-hub.se/10.1029/2019sw002267
Coupled Sun-to-Earth models represent a key part of the future development of space weather forecasting. With respect to predicting the state of the thermosphere and ionosphere, there has been a recent paradigm shift; it is now clear that any self-respecting model of this region needs to include some representation of forcing from the lower atmosphere, as well as solar and geomagnetic forcing. Here we assess existing modeling capability and set out a road map for the important next steps needed to ensure further advances. These steps include a model verification strategy, analysis of the impact of nonhydrostatic dynamical cores, and a cost-benefit analysis of model chemistry for weather and climate applications.

A DAILY DETERMINATION OF BZ USING THE RUSSELL-MCPHERRON EFFECT TO FORECAST GEOMAGNETIC ACTIVITY

B.V. **Jackson**, H.-S. Yu, A. Buffington, P.P. Hick, M. Tokumaru, K. Fujiki, J. Kim, J. Yun
Space Weather **2019**
sci-hub.se/10.1029/2018SW002098
Since the middle of the last decade, UCSD has incorporated magnetic field data in its ISEE IPS tomographic analysis. These data are extrapolated upward from the solar surface using the Current Sheet Source Surface (CSSS) model (Zhao & Hoeksema, 1995) to provide predictions of the interplanetary field in RTN coordinates. Over the years this technique has become ever more sophisticated, and allows different types of magnetogram data (SOLIS, GONG, etc.,) to be incorporated in the field extrapolations. At Earth, these fields can be displayed in a variety of ways, including GSM Bx, By, and Bz coordinates. Displayed daily, the CSSS model-derived GSM Bz shows a significant positive correlation with the low-resolution (few day variation) in-situ measurements of the Bz field. The nano-Tesla variations of Bz maximize in spring and fall as Russell and McPherron (1973) have shown. More

significantly, we find that the daily variations are correlated with geomagnetic Kp and Dst index variations, and that a decrease from positive to negative Bz has a high correlation with minor-to-moderate geomagnetic storm activity, as defined by NOAA Space Weather Prediction Center planetary Kp values. Here we provide an eleven-year study of the predicted Bz field, from the extrapolation of the GONG-magnetograms. We provide a skill-score analysis of the technique's geomagnetic storm prediction capability, which allows forecasts of moderate enhanced geomagnetic storm activity. UCSD and the Korean Space Weather Center currently operate a website that predicts this low-resolution GSM Bzfield component variation several days in advance.

PRESTO – Predictability of the Variable Solar-Terrestrial Coupling Pillar 1: Sun, interplanetary space and geospace

L. C. A. **Jaynes**1, E. Kilpua2 and S. Patsourakos3

SCOSTEP__PRESTO Newsletter **2020 File**

Validation for solar wind prediction at Earth: Comparison of coronal and heliospheric models installed at the CCMC

L. K. **Jian**, P. J. MacNeice, A. Taktakishvili, D. Odstrcil, B. Jackson, H.-S. Yu, P. Riley, I. V. Sokolov, R. M. Evans

Space Weather Volume 13, Issue 5 May **2015** Pages 316–338

Multiple coronal and heliospheric models have been recently upgraded at the Community Coordinated Modeling Center (CCMC), including the Wang-Sheeley-Arge (WSA)-Enlil model, MHD-Around-a-Sphere (MAS)-Enlil model, Space Weather Modeling Framework (SWMF), and heliospheric tomography using interplanetary scintillation data. To investigate the effects of photospheric magnetograms from different sources, different coronal models, and different model versions on the model performance, we run these models in 10 combinations. Choosing seven Carrington rotations in 2007 as the time window, we compare the modeling results with the Operating Mission as Nodes on the Internet data for near-Earth space environment during the late declining phase of solar cycle 23. Visual comparison is proved to be a necessary addition to the quantitative assessment of the models' capabilities in reproducing the time series and statistics of solar wind parameters. The MAS-Enlil model captures the time patterns of solar wind parameters better, while the WSA-Enlil model matches with the time series of normalized solar wind parameters better. Models generally overestimate slow wind temperature and underestimate fast wind temperature and magnetic field. Using improved algorithms, we have identified magnetic field sector boundaries (SBs) and slow-to-fast stream interaction regions (SIRs) as focused structures. The success rate of capturing them and the time offset vary largely with models. For this quiet period, the new version of MAS-Enlil model works best for SBs, while heliospheric tomography works best for SIRs. The new version of SWMF with more physics added needs more development. General strengths and weaknesses for each model are diagnosed to provide an unbiased reference to model developers and users.

Different contributions to space weather and space climate from different big solar active regions

Jie **Jiang**, Qiao Song, Jing-Xiu Wang, Tunde Baranyi

ApJ **871** 16 **2019**

https://arxiv.org/pdf/1901.00116.pdf

http://iopscience.iop.org/article/10.3847/1538-4357/aaf64a/pdf

The purpose of this paper is to show that large active regions (ARs) with different magnetic configurations have different contributions to short-term and long-term variations of the Sun. As a case study, the complex δ-type AR 12673 and the simple β-type AR 12674 are investigated in detail. Since the axial dipole moment at cycle minimum determines the amplitude of the subsequent cycle and space climate, we have assimilated the individual observed magnetic configurations of these two ARs into a surface flux transport model to compare their contributions to the axial dipole moment D. We find that AR 12673 has a significant effect on D at the end of the cycle, making it weaker because of the abnormal and complicated magnetic polarities. An initial strongly positive D ends up with a strongly negative value. The flare-poor AR 12674 has a greater contribution to the long-term axial dipole moment than the flare-rich AR 12673. We then carry out a statistical analysis of ARs larger than 800 μHem from 1976 to 2017. We use the flare index FI and define an axial dipole moment index DI to quantify the effects of each AR on space weather and space climate, respectively. Whereas the FI has a strong dependence on the magnetic configuration, the DI shows no such dependence. The DI is mainly determined by the latitudinal location and the latitudinal separation of the positive and negative magnetic fluxes of the ARs. Simple ARs have the same possibility as complex ARs to produce big DI values affecting space climate. **2017 August 28 – September 10**

In Situ Data and Effect Correlation During September 2017 Solar Particle Event

P. **Jiggens**, C. Clavie, H. Evans, T. P. O'Brien, O. Witasse, A. L. Mishev …….

Space Weather **2019**
https://doi.org/10.1029/2018SW001936
Solar energetic particles are one of the main sources of particle radiation seen in space. In the first part of September 2017 the most active solar period of cycle 24 produced four large X-class flares and a series of (interplanetary) coronal mass ejections, which gave rise to radiation storms seen over all energies and at the ground by neutron monitors. This paper presents comprehensive cross comparisons of in situ radiation detector data from near-Earth satellites to give an appraisal on the state of present data processing for monitors of such particles. Many of these data sets have been the target of previous cross calibrations, and this event with a hard spectrum provides the opportunity to validate these results. As a result of the excellent agreement found between these data sets and the use of neutron monitor data, this paper also presents an analytical expression for fluence spectrum for the event. Derived ionizing dose values have been computed to show that although there is a significant high-energy component, the event was not particularly concerning as regards dose effects in spacecraft electronics. Several sets of spacecraft data illustrating single event effects are presented showing a more significant impact in this regard. Such a hard event can penetrate thick shielding; human dose quantities measured inside the International Space Station and derived through modeling for aircraft altitudes are also presented. Lastly, simulation results of coronal mass ejection propagation through the heliosphere are presented along with data from Mars-orbiting spacecraft in addition to data from the Mars surface.

The magnitude and effects of extreme solar particle events

Piers **Jiggens***, Marc-Andre Chavy-Macdonald, Giovanni Santin, Alessandra Menicucci, Hugh Evans and Alain Hilgers
J. Space Weather Space Clim. 4 (**2014**) A20
http://www.swsc-journal.org/articles/swsc/pdf/2014/01/swsc130038.pdf
The solar energetic particle (SEP) radiation environment is an important consideration for spacecraft design, spacecraft mission planning and human spaceflight. Herein is presented an investigation into the likely severity of effects of a very large Solar Particle Event (SPE) on technology and humans in space. Fluences for SPEs derived using statistical models are compared to historical SPEs to verify their appropriateness for use in the analysis which follows. By combining environment tools with tools to model effects behind varying layers of spacecraft shielding it is possible to predict what impact a large SPE would be likely to have on a spacecraft in Near-Earth interplanetary space or geostationary Earth orbit. Also presented is a comparison of results generated using the traditional method of inputting the environment spectra, determined using a statistical model, into effects tools and a new method developed as part of the ESA SEPEM Project allowing for the creation of an effect time series on which statistics, previously applied to the flux data, can be run directly. The SPE environment spectra is determined and presented as energy integrated proton fluence (cm^{-2}) as a function of particle energy (in MeV). This is input into the SHIELDOSE-2, MULASSIS, NIEL, GRAS and SEU effects tools to provide the output results. In the case of the new method for analysis, the flux time series is fed directly into the MULASSIS and GEMAT tools integrated into the SEPEM system. The output effect quantities include total ionising dose (in rads), non-ionising energy loss (MeV g^{-1}), single event upsets (upsets/bit) and the dose in humans compared to established limits for stochastic (or cancer-causing) effects and tissue reactions (such as acute radiation sickness) in humans given in grey-equivalent and sieverts respectively.

Solar cycle and seasonal variations of the GPS phase scintillation at high latitudes

Yaqi **Jin**1*, Wojciech J. Miloch1, Jøran I. Moen1,2 and Lasse B.N. Clausen
J. Space Weather Space Clim. **2018**, 8, A48
https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc170089.pdf
We present the long-term statistics of the GPS phase scintillation in the polar region (70°–82° magnetic latitude) by using the GPS scintillation data from Ny-Ålesund for the period 2010–2017. Ny-Ålesund is ideally located to observe GPS scintillations modulated by the ionosphere cusp dynamics. The results show clear solar cycle and seasonal variations, with the GPS scintillation occurrence rate being much higher during solar maximum than during solar minimum. The seasonal variations show that scintillation occurrence rate is low during summer and high during winter. The highest scintillation occurrence rate is around magnetic noon except for December 2014 (solar maximum) when the nightside scintillation occurrence rate exceeds the dayside one. In summer, the dayside scintillation region is weak and there is a lack of scintillations in the nightside polar cap. The most intriguing features of the seasonal variations are local minima in the scintillation occurrence rate around winter solstices. They correspond to local minima in the F2 peak electron density. The dayside scintillation region migrates equatorward from summer to winter and retreats poleward from winter to summer repetitively in a magnetic latitude range of 74°–80°. This latitudinal movement is likely due to the motion of the cusp location due to the tilt of the Earth's magnetic field and the impact of the sunlight.

Formation and Evolution of Low-Latitude F Region Field-Aligned Irregularities During the 7–8 September 2017 Storm: Hainan Coherent Scatter Phased Array Radar and Digisonde Observations

Han **Jin**, Shasha Zou, Gang Chen, Chunxiao Yan, Shaodong Zhang, Guotao Yang

http://sci-hub.tw/10.1029/2018SW001865

In this paper, we present a study of the low-latitude field-aligned irregularities formation and evolution during the 7–8 September 2017 geomagnetic storm by analyzing data of the very high frequency coherent radar installed at Fuke, Hainan Island of China (19.5°N, 109.1°E; magnetic latitude 9.58°N) and a colocated Digisonde Portable Sounder. The prompt penetration of eastward interplanetary electric field associated with sudden southward turning of the interplanetary magnetic field Bz resulted in large ascent of the Flayer, making conducive conditions at the bottomside of the layer for the growth of Rayleigh-Taylor instability and the development of the plasma irregularities in the postsunset hours. The irregularities persisted into the postmidnight sector when the southward interplanetary magnetic field Bz gradually decreased to the quiet time values. In addition, the base height of F layer at Fuke also showed a large elevation after midnight during two consecutive substorm onsets, suggesting that the substorm-induced overshielding penetration electric field may take over and modify the ambient zonal electric field in low-latitude ionosphere and induce the irregularities in the postmidnight sector. Moreover, different from the quiet time eastward movement of the irregularities observed over Fuke, the storm time irregularities displayed no zonal drift at the initial period and subsequently began drifting westward. The reversal of background plasma zonal drift velocity observed by Hainan digisonde characterized the storm time zonal drift pattern of the irregularities.

White House Releases National Space Weather Strategy and Action Plan

Seth **Jonas**, Eoin D. McCarron

Space Weather Volume 14, Issue 2 February **2016** Pages 54–55

SWQuarterly Volume 13, Issue 1, **2016**

http://onlinelibrary.wiley.com/doi/10.1002/SWQv13i001/epdf

White House releases National Space Weather Strategy and Action Plan

Federal interagency space weather policy articulates the Federal Government role in space weather

The strategy and action plan facilitate enhancement of national preparedness and resilience

State of the Art in Space Weather Services and Forecasting

Joselyn, J. A.

Space Storms and Space Weather Hazards, Proceedings of the NATO Advanced Study Institute on Space Storms and Space Weather Hazards, held in Hersonissos, Crete, Greece, 19-29 June, 2000. Edited by I.A. Daglis. Published by Kluwer Academic Publishers, **2001**, p.419

Exploring Contingency Skill Scores Based on Event Sizes

S. W. **Kahler** , H. Darsey

Space Weather e2020SW002604 **2021 File**

https://doi.org/10.1029/2020SW002604

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020SW002604

Space weather forecasts are generally made for events with an arbitrary size threshold imposed on an event statistical size distribution which is likely described by a power law. This is the case for solar energetic ($E > 10$ MeV) particle (SEP) events, which have a differential power law exponent of $\gamma = 1.2$. Event forecasts are usually evaluated by skill scores using a contingency table that matches the forecasted events against observed events independently of the event sizes. Each observed event is either a forecasted hit or a miss, and each forecasted event is either an observed hit or a false alarm. However, for SEP events and most other space weather parameters the event size is a critical factor for the user. It is more important that large events be well forecasted than threshold events. In addition, false alarms may be useful when they match observed events just below the forecast threshold. We explore a forecast evaluation scheme to incorporate the event size within the usual format of a binary contingency table to evaluate model performance. The scheme is applied to three different input options of a recently published evaluation of the Proton Prediction System (PPS) for SEP events to show differences between numbers-based and intensity-based skill scores of the PPS. We demonstrate how identical skill scores can result from models with extremely different performances of event intensity forecasts. The scheme requires model validation and would benefit from testing with other space weather applications.

Forecasting Solar Energetic Particle (SEP) events with Flare X-ray peak ratios

Stephen W. **Kahler** and Alan. G. Ling

J. Space Weather Space Clim. **2018**, 8, A47

https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc180013.pdf

Solar flare X-ray peak fluxes and fluences in the 0.1–0.8 nm band are often used in models to forecast solar energetic particle (SEP) events. Garcia (2004) [Forecasting methods for occurrence and magnitude of proton storms with solar soft X rays, Space Weather, 2, S02002, 2004] used ratios of the 0.05–0.4 and 0.1–0.8 nm bands of the X-ray instrument on the GOES spacecraft to plot inferred peak flare temperatures versus peak 0.1–0.8 nm fluxes for flares from 1988 to 2002. Flares associated with E > 10 MeV SEP events of >10 proton flux units (pfu) had statistically lower peak temperatures than those without SEP events and therefore offered a possible empirical forecasting tool for SEP events. We review the soft and hard X-ray flare spectral variations as SEP event forecast tools and repeat Garcia's work for the period 1998–2016, comparing both the peak ratios and the ratios of the preceding 0.05–0.4 nm peak fluxes to the later 0.1–0.8 nm peak fluxes of flares >M3 to the occurrence of associated SEP events. We divide the events into eastern and western hemisphere sources and compare both small (1.2–10 pfu) and large (≥300 pfu) SEP events with those of >10 pfu. In the western hemisphere X-ray peak ratios are statistically lower for >10 pfu SEP events than for non-SEP events and are even lower for the large (>300 pfu) events. The small SEP events, however, are not distinguished from the non-SEP events. We discuss the possible connections between the flare X-ray peak ratios and associated coronal mass ejections that are presumed to be the sources of the SEPs.

Forecasting E > 50-MeV proton events with the proton prediction system (PPS)

Stephen W. **Kahler**1*, Stephen M. White1 and Alan G. Ling

J. Space Weather Space Clim. **2017**, 7, A27

https://www.swsc-journal.org/articles/swsc/pdf/2017/01/swsc170016.pdf

Forecasting solar energetic (E > 10-MeV) particle (SEP) events is an important element of space weather. While several models have been developed for use in forecasting such events, satellite operations are particularly vulnerable to higher-energy (≥50-MeV) SEP events. Here we validate one model, the proton prediction system (PPS), which extends to that energy range. We first develop a data base of E ≥ 50-MeV proton events >1.0 proton flux units (pfu) events observed on the GOES satellite over the period 1986–2016. We modify the PPS to forecast proton events at the reduced level of 1 pfu and run PPS for four different solar input parameters: (1) all ≥M5 solar X-ray flares; (2) all ≥200 sfu 8800-MHz bursts with associated ≥M5 flares; (3) all ≥500 sfu 8800-MHz bursts; and (4) all ≥5000 sfu 8800-MHz bursts. The validation contingency tables and skill scores are calculated for all groups and used as a guide to use of the PPS. We plot the false alarms and missed events as functions of solar source longitude, and argue that the longitude-dependence employed by PPS does not match modern observations. Use of the radio fluxes as the PPS driver tends to result in too many false alarms at the 500 sfu threshold, and misses more events than the soft X-ray predictor at the 5000 sfu threshold.

Table 1. The E > 50 MeV 10-pfu events, flare associations, and PPS outcomes (1986-2014)

Dynamic SEP event probability forecasts

S. W. **Kahler** and A. Ling

Space Weather Volume 13, Issue 10 (pages 665–675) **2015** DOI: 10.1002/2015SW001222

http://sci-hub.cc/10.1002/2015SW001222

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2015SW001222

The forecasting of solar energetic particle (SEP) event probabilities at Earth has been based primarily on the estimates of magnetic free energy in active regions and on the observations of peak fluxes and fluences of large (≥ M2) solar X-ray flares. These forecasts are typically issued for the next 24 h or with no definite expiration time, which can be deficient for time-critical operations when no SEP event appears following a large X-ray flare. It is therefore important to decrease the event probability forecast with time as a SEP event fails to appear. We use the NOAA listing of major (≥10 pfu) SEP events from 1976 to 2014 to plot the delay times from X-ray peaks to SEP threshold onsets as a function of solar source longitude. An algorithm is derived to decrease the SEP event probabilities with time when no event is observed to reach the 10 pfu threshold. In addition, we use known SEP event size distributions to modify probability forecasts when SEP intensity increases occur below the 10 pfu event threshold. An algorithm to provide a dynamic SEP event forecast, Pd, for both situations of SEP intensities following a large flare is derived. **04/05/2000, 12/06/2006, 02/15/2011, 08/04/2011, 09/07/2011, 07/07/2012,**

See Kahler in the SEP section

Diminishing activity of recent solar cycles (22–24) and their impact on geospace

Bharati **Kakad**, Amar Kakad, Durbha Sai Ramesh and Gurbax S. Lakhina

J. Space Weather Space Clim. **2019**, 9, A01

https://www.swsc-journal.org/articles/swsc/pdf/2019/01/swsc180016.pdf

This study examines the variation of different energies linked with the Sun and the Earth's magnetosphere-ionosphere systems for solar cycles (SCs) 22–24 for which the gradual decrease in the solar activity is noticed. Firstly, we investigated the variation of solar magnetic energy density (SMED) for SCs 21–24 and its relation to the solar activity. We observed distinct double peak structures in SMED for the past four SCs, 21–24. This feature is consistent with noticeable asymmetry in their two peaks. For SCs 22–24 a significant decrease is observed in the integrated SMED of each SC. This reduction is 37% from SCs 22 to 23 and 51% from SCs 23 to 24, which indicates substantial weakening of Sun's magnetic field for SC 24. Also, the magnetic, kinetic, and thermal energy densities at the Earth's bow-shock nose are found to be considerably low for the SC 24. We examined the solar wind Alfven speed, magnetosonic Mach number, solar wind-magnetosphere energy coupling parameter (ε), and the Chapman-Ferraro magnetopause distance (LCF) for the SCs 22–24. The estimated maximum stand-off magnetopause distance is larger for SC 24 (LCF ≤ 10.6 RE) as compared to SC 23 (LCF ≤ 10.2 RE) and SC 22 (LCF ≤ 9.8 RE). The solar wind Alfven speeds during SCs 22 and 23 are in the same range and do not exceed ≈73 km/s whereas, it is below 57 km/s for SC 24. A lower bound of solar wind magnetosonic Mach number for SC 24 is larger (M ≥ 6.9) as compared to SC 22 (M ≥ 5.9) and SC 23 (M ≥ 6). We noticed weakening in the energy coupling parameter for SC 24, which resulted in substantial (15%–38%) decrease in average strength of high latitude ionospheric (AE), low latitude magnetospheric (Dst) and equatorial ionospheric (EEJ) current systems in comparison with SC 23. Subsequently, a reduction of ≈30% is manifested in the high latitude Joule heating for SC 24. Overall this study indicates the significant step down in various energies at Sun, Earth's bow-shock, and near Earth environment for current SC 24, which will have important implication on our Earth's atmosphere-ionosphere-magnetosphere system.

Monitoring, analysis and post-casting of the Earth's particle radiation environment during February 14–March 5, 2014

Vladimir **Kalegaev**1*, Mikhail Panasyuk1, Irina Myagkova1, Yulia Shugay1, Natalia Vlasova1, Wera Barinova1, Evgenia Beresneva1, Sergey Bobrovnikov1, Valery Eremeev1, Sergey Dolenko1, Ilya Nazarkov1, Minh Nguyen1 and Arnaud Prost2

J. Space Weather Space Clim. **2019**, 9, A29

https://www.swsc-journal.org/articles/swsc/pdf/2019/01/swsc180008.pdf

Internet-based system of Space Monitoring Data Center (SMDC) of Skobeltsyn Institute of Nuclear Physics of Moscow State University (SINP MSU) has been developed to predict and analyze radiation conditions in near-Earth space. This system contains satellite measurement databases and operational models and devoted to collect, store and process space weather monitoring data in the near real-time. SMDC operational services acquire data from ACE, SDO, GOES, Electro-L, Meteor-M satellites and use them for forecasting, now-casting and post-casting of space weather factors. This paper is intended to give overview of operational services of SMDC Internet-based system and demonstrate their possibilities and limitations to analyze space weather phenomena and predict radiation and geomagnetic conditions in the near-Earth space during February 14–March 5, 2014. This prolonged period of high level solar and geomagnetic activity demonstrates various manifestations of the space weather: solar proton events, geomagnetic storms and outer radiation belt (RB) dynamics. Solar sources of interplanetary space disturbances and their influence on geomagnetic and radiation state of the Earth's magnetosphere were described using output coming from SMDC' Web-based applications. Validation of SMDC's operational models was performed based on the quality of description of the physical conditions in near-Earth space during space weather events observed from **February 14 to March 5, 2014**. The advantages and disadvantages of SMDC operational services are illustrated and discussed based on comparison with data obtained from satellites.

Unexpected space weather causing the reentry of 38 Starlink satellites in February 2022

Ryuho **Kataoka**1,2,3*, Daikou Shiota4, Hitoshi Fujiwara5, Hidekatsu Jin4, Chihiro Tao4, Hiroyuki Shinagawa4 and Yasunobu Miyoshi6

J. Space Weather Space Clim. **2022**, 12, 41

https://www.swsc-journal.org/articles/swsc/pdf/2022/01/swsc220018.pdf

The accidental reentry of 38 Starlink satellites occurred in early February 2022, associated with the occurrence of moderate magnetic storms. A poorly understood structure of Coronal Mass Ejections (CMEs) caused the magnetic storms at unexpected timing. Therefore, a better understanding of minor CME structures is necessary for the modern space weather forecast. During this event, the "up to 50%" enhancement of air drag force was observed at ~200 km altitude, preventing the satellites' safety operations. Although the mass density enhancement predicted by the NRLMSIS2.0 empirical model is less than 25% under the present moderate magnetic storms, the real-time GAIA simulation showed a mass density enhancement of up to 50%. Further, the real-time GAIA simulation suggests that the actual thermospheric disturbances at 200 km altitude may occur with larger amplitude in a broader area than previously thought. **29 Jan 2022, 2-5 Feb 2022**

Radiation Dose Nowcast for the Ground Level Enhancement on 10-11 September 2017

Ryuho **Kataoka**1,2, Tatsuhiko Sato3 , Shoko Miyake4 , Daikou Shiota5,6, and Yûki Kubo5

Space Weather, **Volume16, Issue7** Pages 917-923 **2018**

http://sci-hub.tw/10.1029/2018SW001874
A ground level enhancement (GLE) event occurred on **10-11 September 2017**, associated with an X8.2 solar flare on the western limb of the Sun. We report the results of our manually conducted nowcast using WASAVIES (WArning System for AVIation Exposure to Solar energetic particles). The maximum radiation dose rate at a flight altitude of 12 km was estimated to be approximately 3 μSv/h, which is less than half of the dose rate due to galactic cosmic rays. We also discuss a possible quasi-parallel shock-acceleration mechanism that may have led to the exceptionally soft proton energy spectrum as GLE events.

Inclined Zenith Aurora over Kyoto on 17 September 1770: Graphical Evidence of Extreme Magnetic Storm

Ryuho **Kataoka** Kiyomi Iwahashi
Space Weather Volume 15, Issue 10 **2017**
sci-hub.tw/10.1002/2017SW001690
Red auroras were observed in Japan during an extreme magnetic storm that occurred on 17 September 1770. We show new evidence that the red aurora extended toward the zenith of Kyoto around midnight. The basic appearance of the historical painting of the red aurora is geometrically reproduced based on the inclination of the local magnetic field and a detailed description in a newly discovered diary. The presence of the inclined zenith aurora over Kyoto suggests that the intensity of the September 1770 magnetic storm is comparable to, or slightly larger than that of the September 1859 Carrington storm.

Historical space weather monitoring of prolonged aurora activities in Japan and in China

Ryuho **Kataoka** Hiroaki Isobe Hisashi Hayakawa …
Space Weather Volume 15, Issue 2 **2017**
sci-hub.tw/10.1002/2016SW001493
Great magnetic storms are recorded as aurora sightings in historical documents. The earliest known example of "prolonged" aurora sightings, with aurora persistent for two or more nights within a 7 day interval at low latitudes, in Japan was documented on **21–23 February 1204** in Meigetsuki, when a big sunspot was also recorded in China. We have searched for prolonged events over the 600 year interval since 620 in Japan based on the catalogue of Kanda [1933] and over the 700 year interval since 581 in China based on the catalogues of Tamazawa et al. (2017) and Hayakawa et al. (2015). Before the Meigetsuki event, a significant fraction of the 200 possible aurora sightings in Sòng dynasty (960–1279) of China was detected at least twice within a 7 day interval and sometimes recurred with approximately the solar rotation period of 27 days. The majority of prolonged aurora activity events occurred around the maximum phase of solar cycles rather than around the minimum, as estimated from the 14C analysis of tree rings. They were not reported during the Oort Minimum (1010–1050). We hypothesize that the prolonged aurora sightings are associated with great magnetic storms resulting from multiple coronal mass ejections from the same active region. The historical documents therefore provide useful information to support estimation of great magnetic storm frequency, which are often associated with power outages and other societal concerns.

Radiation dose forecast of WASAVIES during ground-level enhancement

Ryuho **Kataoka**1,*, Tatsuhiko Sato2, Yûki Kubo3, Daikou Shiota4, Takao Kuwabara5, Seiji Yashiro6 andHiroshi Yasuda7
Space Weather, Volume 12, Issue 6, pages 380–386, June **2014**
Solar energetic particles (SEPs) sometimes induce powerful air showers that significantly increase the radiation dose at flight altitudes. In order to provide information of such a space radiation hazard to aircrew, a forecast model is developed for WASAVIES (Warning System of Aviation Exposure to SEP), based on the focused transport equation of solar protons and Monte Carlo particle transport simulation of the air shower. WASAVIES gives a simple and fast way to predict the time profile of dose rate during ground-level enhancements.

OSPREI: A Coupled Approach to Modeling CME-Driven Space Weather With Automatically Generated, User-Friendly Outputs

C. **Kay**, M. L. Mays,Y. M. Collado-Vega
Space Weather e2021SW002914 **2022**
https://arxiv.org/pdf/2109.06960.pdf
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021SW002914
Coronal mass ejections (CMEs) drive space weather activity at Earth and throughout the solar system. Current CME-related space weather predictions rely on information reconstructed from coronagraphs, sometimes from only a single viewpoint, to drive a simple interplanetary propagation model, which only gives the arrival time or limited additional information. We present the coupling of three established models into OSPREI (Open Solar Physics Rapid Ensemble Information), a new tool that describes Sun-to-Earth CME behavior, including the location, orientation, size, shape, speed, arrival time, and internal thermal and magnetic properties, on the timescale needed

for forecasts. First, Forecasting a CME's Altered Trajectory (ForeCAT) describes the trajectory that a CME takes through the solar corona. Second, ANother Type of Ensemble Arrival Time Results simulates the propagation, including expansion and deformation, of a CME in interplanetary space and determines the evolution of internal properties via conservation laws. Finally, ForeCAT In situ Data Observer produces in situ profiles for a CME's interaction with a synthetic spacecraft. OSPREI includes ensemble modeling by varying each input parameter to probe any uncertainty in their values, yielding probabilities for all outputs. Standardized visualizations are automatically generated, providing easily accessible, essential information for space weather forecasting. We show OSPREI results for a CMEs observed in the corona on **22 April and 09 May 2021**. We approach these CME as a forecasting proof-of-concept, using information analogous to what would be available in real time rather than fine-tuning input parameters to achieve a best fit for a detailed scientific study. The OSPREI "prediction" shows good agreement with the arrival time and in situ properties. **21 April 2021, 09 May 2021**

Comparison of Deep Learning Techniques to Model Connections Between Solar Wind and Ground Magnetic Perturbations

Amy M. **Keesee**1*, Victor Pinto1, Michael Coughlan1, Connor Lennox2, Md Shaad Mahmud2 and Hyunju K. Connor3

Front. Astron. Space Sci., 06 October **2020** |
https://doi.org/10.3389/fspas.2020.550874
https://www.frontiersin.org/articles/10.3389/fspas.2020.550874/full

Geomagnetically induced currents (GIC) can drive power outages and damage power grid components while also affecting pipelines and train systems. Developing the ability to predict local GICs is important to protecting infrastructure and limiting the impact of geomagnetic storms on public safety and the economy. While GIC data is not readily available, variations in the magnetic field, dB/dt, measured by ground magnetometers can be used as a proxy for GICs. We are developing a set of neural networks to predict the east and north components of the magnetic field, BE and BN, from which the horizontal component, BH, and its variation in time, dBH/dt, are calculated. We apply two techniques for time series analysis to study the connection of solar wind and interplanetary magnetic field properties obtained from the OMNI dataset to the ground magnetic field perturbations. The analysis techniques include a feed-forward artificial neural network (ANN) and a long-short term memory (LSTM) neural network. Here we present a comparison of both models' performance when predicting the BH component of the Ottawa (OTT) ground magnetometer for the year 2011 and 2015 and then when attempting to reconstruct the time series of BH for two geomagnetic storms that occurred on **5 August 2011** and **17 March 2015**.

Geomagnetically Induced Currents at Middle Latitudes: 1. Quiet-time Variability

A. C. **Kellerman**, Ryan Mcgranaghan, Jacob Bortnik, Brett A. Carter, Joseph Hughes, Robert F. Arritt, Karthik Venkataramani, Charles H. Perry, Jackson McCormick, Chigomezyo M. Ngwira, Morris Cohen, Jia Yue

Space Weather e2021SW002729 **2021**
https://doi.org/10.1029/2021SW002729

Geomagnetically induced currents (GICs) at middle latitudes have received increased attention after reported power-grid disruptions due to geomagnetic disturbances. However, quantifying the risk to the electric power grid at middle latitudes is difficult without understanding how the GIC sensors respond to geomagnetic activity on a daily basis. Therefore, in this study the question "Do measured GICs have distinguishable and quantifiable long- and short-period characteristics?" is addressed. The study focuses on the long-term variability of measured GIC, and establishes the extent to which the variability relates to quiet-time geomagnetic activity. GIC quiet-day curves (QDCs) are computed from measured data for each GIC node, covering all four seasons, and then compared with the seasonal variability of Thermosphere-Ionosphere- Electrodynamics General Circulation Model (TIE-GCM)-simulated neutral wind and height-integrated current density. The results show strong evidence that the middle-latitude nodes routinely respond to the tidal-driven Sq variation, with a local time and seasonal dependence on the the direction of the ionospheric currents, which is specific to each node. The strong dependence of GICs on the Sq currents demonstrates that the GIC QDCs may be employed as a robust baseline from which to quantify the significance of GICs during geomagnetically active times and to isolate those variations to study independently. The QDC-based significance score computed in this study provides power utilities with a node-specific measure of the geomagnetic significance of a given GIC observation. Finally, this study shows that the power grid acts as a giant sensor that may detect ionospheric current systems.

From terrestrial weather to space weather through the history of scintillation

Historical survay

Emily F. **Kerrison**, Ron D. Ekers, John Morgan, Rajan Chhetri

IAU Symposium 390 **2024**

https://arxiv.org/pdf/2412.19816

Recent observations of interplanetary scintillation (IPS) at radio frequencies have proved to be a powerful tool for probing the solar environment from the ground. But how far back does this tradition really extend? Our survey of the literature to date has revealed a long history of scintillating observations, beginning with the oral traditions of Indigenous peoples from around the globe, encompassing the works of the Ancient Greeks and Renaissance scholars, and continuing right through into modern optics, astronomy and space science. We outline here the major steps that humanity has taken along this journey, using scintillation as a tool for predicting first terrestrial, and then space weather without ever having to leave the ground.

Study of cosmic ray intensity and geomagnetic storms with solar wind parameters during the period 1998–2005

Hema **Kharayat,** Lalan Prasad

Astrophysics and Space Science January **2017**, 362:20

http://link.springer.com/article/10.1007/s10509-016-2996-5?wt_mc=alerts.TOCjournals

The aim of this paper is to study the effect of solar wind parameters (solar wind speed VV, plasma flow pressure, and plasma density) on cosmic ray intensity and on geomagnetic storms for the period 1998–2005 (solar cycle 23). A Chree analysis by the superposed epoch method has been done for the study. From the present study we have found that the solar wind speed is a highly effective parameter in producing cosmic ray intensity decreases and geomagnetic storms. No time lag is found between cosmic ray intensity decreases, geomagnetic storms, and peak value of solar wind speed. Further, we have found that the plasma flow pressure is effectively correlated with geomagnetic storms but it is weakly correlated with cosmic ray intensity. The cosmic ray intensity and geomagnetic storms are found to be weakly correlated with plasma density. The decrease in cosmic ray intensity and geomagnetic storms takes place one day after the peak values of plasma flow pressure and plasma density. There is a time lag of one day between solar wind parameters (plasma flow pressure and plasma density) and cosmic ray intensity decrease, geomagnetic storms. Also, we have found a high correlation of cosmic ray intensity and geomagnetic storms with the product of interplanetary magnetic field BB and solar wind speed VV i.e. B·VB·V. This study may be useful in predicting the space-weather phenomena.

Forecasting the Structure and Orientation of Earthbound Coronal Mass Ejections

E. K. J. **Kilpua** N. Lugaz L. Mays M. Temmer

Space Weather **2019**

https://doi.org/10.1029/2018SW001944

sci-hub.tw/10.1029/2018SW001944

Coronal Mass Ejections (CMEs) are the key drivers of strong to extreme space weather storms at the Earth that can have drastic consequences for technological systems in space and on ground. The ability of a CME to drive geomagnetic disturbances depends crucially on the magnetic structure of the embedded flux rope, which is thus essential to predict. The current capabilities in forecasting in advance (at least half-a-day before) the geoeffectiveness of a given CME is however severely hampered by the lack of remote-sensing measurements of the magnetic field in the corona and adequate tools to predict how CMEs deform, rotate and deflect during their travel through the coronal and interplanetary space as they interact with the ambient solar wind and other CMEs. These problems can lead not only to over- or underestimation of the severity of a storm, but also to forecasting “misses" and “false alarms" that are particularly difficult for the end-users. In this paper, we discuss the current status and future challenges and prospects related to forecasting of the magnetic structure and orientation of CMEs. We focus both on observational and modeling (first-principle and semi-empirical) based approaches, and discuss the space- and ground-based observations that would be the most optimal for making accurate space weather predictions. We also cover the gaps in our current understanding related to the formation and eruption of the CME flux rope and physical processes that govern its evolution in the variable ambient solar wind background that complicate the forecasting.

Geoeffective Properties of Solar Transients and Stream Interaction Regions **Review**

E. K. J. **Kilpua,** A. Balogh, R. von Steiger,Y. D. Liu

Space Science Reviews Volume 212, Issue 3–4, pp 1271–1314 **2017**

https://link.springer.com/content/pdf/10.1007%2Fs11214-017-0411-3.pdf

Interplanetary Coronal Mass Ejections (ICMEs), their possible shocks and sheaths, and co-rotating interaction regions (CIRs) are the primary large-scale heliospheric structures driving geospace disturbances at the Earth. CIRs are followed by a faster stream where Alfvénic fluctuations may drive prolonged high-latitude activity. In this paper we highlight that these structures have all different origins, solar wind conditions and as a consequence, different geomagnetic responses. We discuss general solar wind properties of sheaths, ICMEs (in particular those showing the flux rope signatures), CIRs and fast streams and how they affect their solar wind coupling efficiency and the resulting magnetospheric activity. We show that there are two different solar wind driving modes: (1) Sheath-like with turbulent magnetic fields, and large Alfvén Mach (MAMA) numbers and dynamic pressure, and (2) flux rope-like with smoothly varying magnetic field direction, and lower MAMA numbers and dynamic pressure. We also summarize the key properties of interplanetary shocks for space weather and how they depend on solar cycle and the driver. **November 20–21, 2003., January 11–13, 2005, December 14–15, 2006, 8-9 March 2008, June 4–5, 2011, 23 July 2013, Oct 02, 2013, July 14, 2014**

A technique for prediction of SPEs from solar radio flux by statistical analysis, ANN and GA

Kyong Nam **Kim**, Sun Ae Sin, Kum Ae Song, Jin Hyok Kong
Astrophys Space Sci (**2018**) 363:170
http://sci-hub.tw/10.1007/s10509-018-3263-8
Solar Radio Flux (SRF) is the significant index in easily evaluating everyday solar activities. From the statistical analysis of SRF at 2800 MHz, 1415 MHz and 610 MHz from 1976 to 1994, and only 111 Solar Proton Events (SPEs) occurring in the same period, we have given the statistical relation between them. In fact, there occurred a total of 131 SPEs in the same period, but we dealt with only 111 SPEs of them, because of lack of SRF data in SGD (2800 MHz, 1415 MHz and 610 MHz). We also discussed the possible parameters of SRF at 2800 MHz, 1415 MHz and 610 MHz for prediction of SPEs by statistical analysis, Artificial Neural Network (ANN) and Genetic Algorithm (GA) using MATLAB. In this study, we used some parameters: the daily total SRF, the overall rate of increase of SRF and SPEs.

Solar radio bursts as a tool for space weather forecasting

Klein, Karl-Ludwig; Matamoros, Carolina Salas; Zucca, Pietro
Comptes rendus - Physique, Volume 19, Issue 1-2, p. 36-42, **2018**.
https://reader.elsevier.com/reader/sd/pii/S1631070518300148?token=D537F952710CF6363FBFFAA0FCDAD2C023FF41B2CE662268302A75A4269C47C6EF93BD3474EEE4AA2545C31B0BFDD8D1
https://www.sciencedirect.com/science/article/pii/S1631070518300148?via%3Dihub
The solar corona and its activity induce disturbances that may affect the space environment of the Earth. Noticeable disturbances come from coronal mass ejections (CMEs), which are large-scale ejections of plasma and magnetic fields from the solar corona, and solar energetic particles (SEPs). These particles are accelerated during the explosive variation of the coronal magnetic field or at the shock wave driven by a fast CME. In this contribution, it is illustrated how full Sun microwave observations can lead to (1) an estimate of CME speeds and of the arrival time of the CME at the Earth, (2) the prediction of SEP events attaining the Earth. **4 Nov 2015**

Timelines as a tool for learning about space weather storms

Delores J. **Knipp**1,2*, Valerie Bernstein1, Kaiya Wahl3 and Hisashi Hayakawa4,5,6
J. Space Weather Space Clim. **2021**, 11, 29
https://www.swsc-journal.org/articles/swsc/pdf/2021/01/swsc200106.pdf
https://doi.org/10.1051/swsc/2021011
Space weather storms typically have solar, interplanetary, geophysical and societal-effect components that overlap in time, making it hard for students and novices to determine cause-and-effect relationships and relative timing. To address this issue, we use timelines to provide context for space weather storms of different intensities. First, we present a timeline and tabular description for the great auroral storms of the last 500 years as an example for space climate. The graphical summary for these 14 events suggests that they occur about every 40–60 years, although the distribution of such events is far from even. One outstanding event in **1770** may qualify as a one-in-500-year auroral event, based on duration. Additionally, we present two examples that describe space weather storms using solar, geospace and effects categories. The first of these is for the prolonged storm sequence of late **January 1938** that produced low-latitude auroras and space weather impacts on mature technology (telegraphs) and on high frequency radio communication for aviation, which was a developing technology. To illustrate storm effects in the space-age, we produce a detailed timeline for the strong **December 2006** geomagnetic storm that impacted numerous space-based technologies for monitoring space weather and for communication and navigation. During this event there were numerous navigations system disturbances and hardware disruptions. We adopt terminology developed in many previous space weather studies and blend it with historical accounts to create graphical timelines to help organize and disentangle the events presented herein.

The 2019 National Space Weather Strategy and Action Plan and Beyond

Delores J. **Knipp** , Jennifer L. Gannon
Space Weather **Volume17, Issue6** June 2019 Pages 794-795
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019SW002254

sci-hub.se/10.1029/2019SW002254
We review, summarize and comment on the 2019 National Space Weather Strategy and Action Plan.

Fall 2018 AGU Editors' Highlights: Living Within the Sun's Stormy Atmosphere

Delores J. **Knipp**
Space Weather **2019**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019SW002154
This article presents highlights in space weather science presented at the American Geophysical Union Literature Review Session at the 2018 Fall AGU.
1. Geomagnetically induced current (GIC) on 6-8 September 2017
2. The 10 September 2017 GLE From Solar Energetic Particles
3. Great Space Weather Storms

Communicating Uncertainty and Reliability in Space Weather Data, Models, and Applications

Delores J. **Knipp**, Michael A. Hapgood, Daniel Welling
Space Weather Volume16, Issue10 October **2018** Pages 1453-1454 https://doi.org/10.1029/2018SW002083
http://sci-hub.tw/10.1029/2018SW002083
Space Weather Journal editors advocate for discussion of uncertainty and reliability in future journal manuscripts and throughout the space weather enterprise.

On the Little-Known Consequences of the 4 August 1972 Ultra-Fast Coronal Mass Ejecta: Facts, Commentary and Call to Action

Delores J. **Knipp**, Brian J. Fraser, M. A. Shea, D. F. Smart
Space Weather **Volume16, Issue11** Pages 1635-1643 **2018**
sci-hub.tw/10.1029/2018SW002024
Today the extreme space weather events of early August 1972 are discussed as benchmarks for Sun-Earth transit times of solar ejecta (14.6 hr) and for solar energetic particle fluxes (10 MeV ion flux > 70000 cm-2 s-1 sr-1). Although the magnetic storm index, Dst, dipped to only -125 nT, the magnetopause was observed within 5.2 RE and the plasmapause within 2 RE. Widespread electric- and communication- grid disturbances plagued North America late on 4 August. There was an additional effect, long buried in the Vietnam War archives that adds credence to the severity of the storm impact: a nearly instantaneous, unintended detonation of dozens of sea mines south of Hai Phong, North Vietnam on 4 August 1972. The US Navy attributed the dramatic event to 'magnetic perturbations of solar storms.' Herein we discuss how such a finding is broadly consistent with terrestrial effects and technological impacts of the 4 August 1972 event and the propagation of major eruptive activity from the Sun to the Earth. We also provide insight into the solar, geophysical and military circumstances of this extraordinary situation. In our view this storm deserves a scientific revisit as a grand challenge for the space weather community, as it provides space-age terrestrial observations of what was likely a Carrington-class storm.

Global Positioning System Energetic Particle Data: The Next Space Weather Data Revolution

Delores J. **Knipp**, Barbara L. Giles
Space Weather Volume 14, Issue 8 August **2016** Pages 526–527
http://onlinelibrary.wiley.com/doi/10.1002/2016SW001483/epdf

Space Weather Quart. Volume 13, Issue 3, p. 2 2016

http://onlinelibrary.wiley.com/doi/10.1002/SWQv13i003/epdf

The May 1967 Great Storm and Radio Disruption Event: Extreme Space Weather and Extraordinary Responses

D. J. **Knipp**1,2, A. C. Ramsay3, E. D. Beard3, A. L. Boright3, W. B. Cade4, I. M. Hewins5, R. McFadden5, W. F. Denig6, L. M. Kilcommons1, M. A. Shea7 and D. F. Smart7
Space Weather Volume 14, Issue 9 September 2016 Pages 614–633 2016 File
Space Weather Quarterly Volume 13, Issue 4 **2016**
http://onlinelibrary.wiley.com/doi/10.1002/swq.12/pdf
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016SW001423

Although listed as one of the most significant events of the last 80 years, the space weather storm of late May 1967 has been of mostly fading academic interest. The storm made its initial mark with a colossal solar radio burst causing radio interference at frequen-cies between 0.01-9.0 GHz and near-simultaneous disruptions of dayside radio communica-tion by intense fluxes of ionizing solar X-rays. Aspects of military control and communica-tion were immediately challenged. Within hours a solar energetic particle event disrupted high frequency communication in the polar cap. Subsequently record-setting geomagnetic and ionospheric storms compounded the disruptions. We explain how the May 1967 storm was nearly one with ultimate societal impact, were it not for the nascent efforts of the United States Air Force in expanding its terrestrial weather monitoring-analysis-warning-prediction efforts into the realm of space weather forecasting. An important and long-lasting outcome of this storm was more formal Department of Defense support for current-day space weather forecasting. This story develops during the rapid rise of solar cycle 20 and the intense Cold War in the latter half of the 20th Century. We detail the events of late May 1967 in the inter-secting categories of solar-terrestrial interactions and the political-military backdrop of the Cold War. This was one of the ―Great Storms‖ of the 20th century, despite the lack of large geomagnetically-induced currents. Radio disruptions like those discussed here warrant the attention of today's radio-reliant, cellular-phone and satellite-navigation enabled world. May 23 1967

Advances in Space Weather Ensemble Forecasting

Delores J. **Knipp**

Space Weather Volume 14, Issue 2 February **2016** Pages 52–53

Space Weather Quarterly Volume 13, Issue 1, 2016
http://onlinelibrary.wiley.com/doi/10.1002/2016SW001366/full

http://onlinelibrary.wiley.com/doi/10.1002/SWQv13i001/epdf

Understanding Space Weather and the Physics Behind It Textbook

By Delores **Knipp**
McGraw-Hill, **2011**; 744 pp.; ISBN: 978-0073408903; $93.33
See **Moldwin, M. (2012), Book Review**: Dolores Knipp's Understanding Space Weather and the Physics Behind It, Space Weather, 10, S08004, 2012

The Impact of Solar Activity on Forecasting the Upper Atmosphere via Assimilation of Electron Density Data

Timothy **Kodikara**, Kefei Zhang, Nicholas Michael Pedatella, Claudia Borries
Space Weather Volume19, Issue5 May **2021** e2020SW002660
This study presents a comprehensive comparison of the impact of solar activity on forecasting the upper atmosphere through assimilation of radio occultation (RO)-derived electron density (Ne) into a physics-based model (TIE-GCM) using an ensemble Kalman filter (KF). Globally abundant RO-derived Ne offers one of the most promising means to test the effect of assimilation on the model forecasted state on a global scale. This study emphasizes the importance of understanding how the assimilation results vary with solar activity, which is one of the main drivers of thermosphere-ionosphere dynamics. This study validates the forecast states with independent RO-derived GRACE (Gravity Recovery and Climate Experiment mission) Ne data. The principal result of the study is that the agreement between forecast Ne and data is better during solar minimum than solar maximum. The results also show that the agreement between data and forecast is mostly better than that of the standalone TIE-GCM driven with observed geophysical indices. The results emphasize that TIE-GCM significantly underestimate Ne in altitudes below 250 km and the assimilation of Ne is not as effective in these lower altitudes as it is in higher altitudes. The results demonstrate that assimilation of Ne significantly impacts the neutral mass density estimates via the KF state vector—the impact is larger during solar maximum than solar minimum relative to a control case that does not assimilate Ne. The results are useful to explain the inherent model bias, to understand the limitations of the data, and to demonstrate the capability of the assimilation technique.

Building a new space weather facility at the National Observatory of Athens

Kontogiannis, Ioannis; Belehaki, Anna; Tsiropoula, Georgia; Tsagouri, Ioanna; Anastasiadis, Anastasios; Papaioannou, Athanasios
Advances in Space Research, Volume 57, Issue 1, p. 418-430. **2016**
http://sci-hub.cc/10.1016/j.asr.2015.10.028

The PROTEAS project has been initiated at the Institute of Astronomy, Astrophysics, Space Applications and Remote Sensing (IAASARS) of the National Observatory of Athens (NOA). One of its main objectives is to provide observations, processed data and space weather nowcasting and forecasting products, designed to support the space weather research community and operators of commercial and industrial systems. The space weather products to be released by this facility, will be the result of the exploitation of ground-based, as well as space-borne observations and of model results and tools already available or under development by IAASARS researchers. The objective will be achieved through: (a) the operation of a small full-disk solar telescope to conduct regular observations of the Sun in the H-alpha line; (b) the construction of a database with near real-time solar observations which will be available to the community through a web-based facility (HELIOSERVER); (c) the development of a tool for forecasting Solar Energetic Particle (SEP) events in relation to observed solar eruptive events; (d) the upgrade of the Athens Digisonde with digital transceivers and the capability of operating in bi-static link mode and (e) the sustainable operation of the European Digital Upper Atmosphere Server (DIAS) upgraded with additional data sets integrated in an interface with the HELIOSERVER and with improved models for the real-time quantification of the effects of solar eruptive events in the ionosphere.

An assessment of the solar irradiance record for climate studies

Greg **Kopp**

J. Space Weather Space Clim. 4 (**2014**) A14

http://www.swsc-journal.org/articles/swsc/pdf/2014/01/swsc130036.pdf

Total solar irradiance, the spatially and spectrally integrated radiant output from the Sun at a mean Sun-Earth distance of 1 astronomical unit, provides nearly all the energy driving the Earth's climate system. Variations in this energy, particularly over long time scales, contribute to changes in Earth's climate and have been linked to historical glaciation and inter-glacial periods as well as having a small effect on more recent global warming. Accurate measurements of solar irradiances require measurements above the Earth's atmosphere. The total solar irradiance spaceborne record began in 1978 and has been uninterrupted since, with over a dozen instruments contributing to the present solar climate data record. I assess the required and achieved accuracies of this record with a focus on its value for climate studies.

Achievements and Challenges in the Science of Space Weather **Review**

Hannu E. J. **Koskinen**, Daniel N. Baker, André Balogh, Tamas Gombosi, Astrid Veronig, Rudolf von Steiger

Space Science Reviews **2017** Volume 212, Issue 3–4, pp 1137–1157 **File**

https://link.springer.com/content/pdf/10.1007%2Fs11214-017-0390-4.pdf

https://link.springer.com/content/pdf/10.1007%2Fs11214-017-0390-4.pdf

In June 2016 a group of 40 space weather scientists attended the workshop on Scientific Foundations of Space Weather at the International Space Science Institute in Bern. In this lead article to the volume based on the talks and discussions during the workshop we review some of main past achievements in the field and outline some of the challenges that the science of space weather is facing today and in the future.

Physics of Space Storms: From the Solar Surface to the Earth **Book**

Hannu **Koskinen**

2011

Read online:

http://www.springerlink.com/content/978-3-642-00310-3/#section=845487&page=1&locus=49

http://www.springer.com/earth+sciences+and+geography/atmospheric+sciences/book/978-3-642-00310-3

This **book** can be interpreted to consist of three parts. The long Chapter 1 forms the first part. It contains a phenomenological introduction to the scene, from the Sun to the Earth, where space weather plays are performed. A reader familiar with basic physics of the Sun, solar wind, magnetosphere and ionosphere can jump over this chapter and only return to it when there is a need to check definitions or concepts introduced there. The second part of the book consists of several chapters on fundamental space plasma physics. While this part is written in a self-consistent way, it is aimed at readers who already have been exposed to basic plasma physics. Chapter 2 briefly introduces the fundamental concepts and tools of plasma physics inherited from both electrodynamics and statistical physics. Chapter 3 reviews the classical guiding center approach to single particle motion and adiabatic invariants, including motion in the dipole field, near a current sheet, and in a time-dependent electric field.

Space Weather: From Solar Eruptions to Magnetospheric Storms **Review**

Koskinen, Hannu E. J.; Huttunen, K. Emilia J.

Geophysical Monograph Series - Volume 165 - Title: Solar Eruptions and Energetic Particles - Editors: N. Gopalswamy, R. Mewaldt, J. Torsti - ISBN 0-87590-430-0 - AGU Code GM1654300. **2006**, p.375

The Coronal Analysis of SHocks and Waves (CASHeW) framework
Kamen A. Kozarev, Alisdair Davey, Alexander Kendrick, Michael Hammer and Celeste Keith
J. Space Weather Space Clim. 2017, 7, A32

Meeting Report: European Commission's Space-Weather Awareness Dialogue,
Krausmann, E., and V. Bothmer
(**2012**), Space Weather, 10, S04006,
Recognizing the need to raise awareness of the risk of severe space-weather impacts on critical infrastructures, the European Commission's Joint Research Centre (JRC), in collaboration with the Directorate-General Enterprise and Industry, organized the Space-Weather Awareness Dialogue, a high-level event held in Brussels, Belgium, on 25–26 October 2011. The dialogue sought to highlight the potential effects of extreme space weather on technological infrastructures both in space and on the ground; to identify related scientific, operational, and policy challenges for disaster prevention, preparedness, and response; and to recommend actions that will reduce the vulnerability of critical infrastructures.

SODA – A tool to predict storm-induced orbit decays for low Earth-orbiting satellites
Sandro **Krauss**1*, Lukas Drescher1, Manuela Temmer2, Barbara Suesser-Rechberger1, Andreas Strasser1 and Sophia Kroisz2
J. Space Weather Space Clim. **2024**, 14, 23
https://doi.org/10.1051/swsc/2024022
https://www.swsc-journal.org/articles/swsc/pdf/2024/01/swsc230087.pdf
Due to the rapidly increasing technological progress in the last decades, the issue of space weather and its influences on our everyday life has more and more importance. Today, satellite-based navigation plays a key role in aviation, logistic, and transportation systems. With the strong rise of the current solar cycle 25 the number and intensity of solar eruptions increasesd. The forecasting tool SODA (Satellite Orbit DecAy) is based on an interdisciplinary analysis of space geodetic observations and solar wind in-situ measurements. It allows the prediction of the impact of in-situ measured interplanetary coronal mass ejections (ICMEs) on the altitude of low Earth-orbiting satellites at 490 km with a lead time of about 20 h, which is defined as the time difference between measuring the minimum Bz component and the orbit decay reaching its maximum. Additionally, it classifies the severeness of the expected geomagnetic storm in the form of the Space Weather G–scale from the National Oceanic and Atmospheric Administration (NOAA). For the establishment and validation of SODA, we examined 360 ICME events over a period of 21 years. Appropriated variations in the thermospheric neutral mass density, were derived mainly from measurements of the Gravity Recovery and Climate Experiment (GRACE) satellite mission. Related changes in the interplanetary magnetic field component Bz were investigated from real-time measurements using data from spacecraft located at the Lagrange point L1. The analysis of the ICME-induced orbit decays and the interplanetary magnetic field showed a strong correlation as well as a time delay between the ICME and the associated thermospheric response. The derived results are implemented in the forecasting tool SODA, which is integrated into the Space Safety Program (Ionospheric Weather Expert Service Center; I.161) of the European Space Agency (ESA).

Thermospheric and geomagnetic responses to interplanetary coronal mass ejections observed by ACE and GRACE: Statistical results
Krauss, S.; Temmer, M.; Veronig, A.; Baur, O.; Lammer, H.
JGR 120, Issue 10, pp. 8848-8860, **2015**
For the period July 2003 to August 2010, the interplanetary coronal mass ejection (ICME) catalogue maintained by Richardson and Cane lists 106 Earth-directed events, which have been measured in situ by plasma and field instruments on board the ACE satellite. We present a statistical investigation of the Earth's thermospheric neutral density response by means of accelerometer measurements collected by the Gravity Recovery And Climate Experiment (GRACE) satellites, which are available for 104 ICMEs in the data set, and its relation to various geomagnetic indices and characteristic ICME parameters such as the impact speed (vmax), southward magnetic field strength (B_z). The majority of ICMEs causes a distinct density enhancement in the thermosphere, with up to a factor of 8 compared to the preevent level. We find high correlations between ICME B_z and thermospheric density enhancements (≈0.9), while the correlation with the ICME impact speed is somewhat smaller (≈0.7). The geomagnetic indices revealing the highest correlations are Dst and SYM-H(≈0.9); the lowest correlations are

obtained for Kp and AE (≈0.7), which show a nonlinear relation with the thermospheric density enhancements. Separating the response for the shock-sheath region and the magnetic structure of the ICME, we find that the Dst and SYM-H reveal a tighter relation to the B_z minimum in the magnetic structure of the ICME, whereas the polar cap indices show higher correlations with the B_z minimum in the shock-sheath region. Since the strength of the B_z component—either in the sheath or in the magnetic structure of the ICME—is highly correlated (≈0.9) with the neutral density enhancement, we discuss the possibility of satellite orbital decay estimates based on magnetic field measurements at L1, i.e., before the ICME hits the Earth magnetosphere. These results are expected to further stimulate progress in space weather understanding and applications regarding satellite operations.

Solar flares as proxy for the young Sun: satellite observed thermosphere response to an X17.2 flare of Earth's upper atmosphere

Krauss, S.; Fichtinger, B.; Lammer, H.; Hausleitner, W.; Kulikov, Yu. N.; Ribas, I.; Shematovich, V. I.; Bisikalo, D.;Lichtenegger, H. I. M.; Zaqarashvili, T. V.; Khodachenko, M. L.; Hanslmeier, A.

Annales Geophysicae, Volume 30, Issue 8, 2012, pp.1129-1141, **2012**

We analyzed the measured thermospheric response of an extreme solar X17.2 flare that irradiated the Earth's upper atmosphere during the so-called Halloween events in late October/early November 2003. We suggest that such events can serve as proxies for the intense electromagnetic and corpuscular radiation environment of the Sun or other stars during their early phases of evolution. We applied and compared empirical thermosphere models with satellite drag measurements from the GRACE satellites and found that the Jacchia-Bowman 2008 model can reproduce the drag measurements very well during undisturbed solar conditions but gets worse during extreme solar events. By analyzing the peak of the X17.2 flare spectra and comparing it with spectra of young solar proxies, our results indicate that the peak flare radiation flux corresponds to a hypothetical Sun-like star or the Sun at the age of approximately 2.3 Gyr. This implies that the peak extreme ultraviolet (EUV) radiation is enhanced by a factor of about 2.5 times compared to today's Sun. On the assumption that the Sun emitted an EUV flux of that magnitude and by modifying the activity indices in the Jacchia-Bowman 2008 model, we obtain an average exobase temperature of 1950 K, which corresponds with previous theoretical studies related to thermospheric heating and expansion caused by the solar EUV flux.

Solar energetic particle cutoff variations during the 29-31 October 2003 geomagnetic storm

Kress, B. T.; Mertens, C. J.; Wiltberger, M.

Space Weather, Vol. 8, No. 5, S05001, **2010**

http://dx.doi.org/10.1029/2009SW000488

At low latitudes to midlatitudes the Earth's magnetic field usually shields the upper atmosphere and spacecraft in low Earth orbit from solar energetic particles (SEPs). During severe geomagnetic storms, distortion of the Earth's field suppresses geomagnetic shielding, allowing SEPs access to the midlatitudes. A case study of the 26–31 October 2003 solar-geomagnetic event is used to examine how a severe geomagnetic storm affects SEP access to the Earth. Geomagnetic cutoffs are numerically determined in model geomagnetic fields using code developed by the Center for Integrated Space Weather Modeling (CISM) at Dartmouth College. The CISM-Dartmouth geomagnetic cutoff model is being used in conjunction with the High Energy and Charge Transport code (HZETRN) at the NASA Langley Research Center to develop a real-time data-driven prediction of radiation exposure at commercial airline altitudes. In this work, cutoff rigidities are computed on global grids and along several high-latitude flight routes before and during the geomagnetic storm. It is found that significant variations in SEP access to the midlatitudes and high latitudes can occur on time scales of an hour or less in response to changes in the solar wind dynamic pressure and interplanetary magnetic field. The maximum suppression of the cutoff is ~1 GV occurring in the midlatitudes during the main phase of the storm. The cutoff is also significantly suppressed by the arrival of an interplanetary shock. The maximum suppression of the cutoff due to the shock is approximately one half of the maximum suppression during the main phase of the storm.

Why do some probabilistic forecasts lack reliability?

Yûki **Kubo**

J. Space Weather Space Clim. **2019**, 9, A17

https://www.swsc-journal.org/articles/swsc/pdf/2019/01/swsc180050.pdf

In this work, we investigate the reliability of the probabilistic binary forecast. We mathematically prove that a necessary, but not sufficient, condition for achieving a reliable probabilistic forecast is maximizing the Peirce Skill Score (PSS) at the threshold probability of the climatological base rate. The condition is confirmed by using artificially synthesized forecast–outcome pair data and previously published probabilistic solar flare forecast models. The condition gives a partial answer as to why some probabilistic forecast system lack reliability, because the system, which does not satisfy the proved condition, can never be reliable. Therefore, the proved condition is very important for the developers of a probabilistic forecast system. The result implies that those who want to develop a reliable probabilistic forecast system must adjust or train the system so as to maximize PSS near the threshold probability of the climatological base rate.

Verification of operational solar flare forecast: Case of Regional Warning Center Japan

Yûki **Kubo**, Mitsue Den, Mamoru Ishii

Journal of Space Weather and Space Climate Volume 7, id.A20, 16 pp. **2017**

https://arxiv.org/pdf/1707.07903.pdf

In this article, we discuss a verification study of an operational solar flare forecast in the Regional Warning Center (RWC) Japan. The RWC Japan has been issuing four-categorical deterministic solar flare forecasts for a long time. In this forecast verification study, we used solar flare forecast data accumulated over 16 years (from 2000 to 2015). We compiled the forecast data together with solar flare data obtained with the Geostationary Operational Environmental Satellites (GOES). Using the compiled data sets, we estimated some conventional scalar verification measures with 95% confidence intervals. We also estimated a multi-categorical scalar verification measure. These scalar verification measures were compared with those obtained by the persistence method and recurrence method. As solar activity varied during the 16 years, we also applied verification analyses to four subsets of forecast-observation pair data with different solar activity levels. We cannot conclude definitely that there are significant performance difference between the forecasts of RWC Japan and the persistence method, although a slightly significant difference is found for some event definitions. We propose to use a scalar verification measure to assess the judgment skill of the operational solar flare forecast. Finally, we propose a verification strategy for deterministic operational solar flare forecasting.

Space weather near Earth and energetic particles: selected results **Review**

K **Kudela**

2013 J. Phys.: Conf. Ser. 409 012017 **File**

Space weather effects have two links to research of energetic particles in space. First, the direct one, connected with the interaction of high energy cosmic particles including galactic, solar cosmic rays, as well as magnetospheric particles, with various materials as satellite systems, atmosphere, ionosphere, airplane systems, human body at high altitudes and in space. Second one, the indirect relations, is checking the relevance of possible forecasts of space weather phenomena according to the data of energetic particles both on the ground and on the satellites and space probes. We review few selected aspects of the second type of relations with references mainly to recent studies, namely (i) progress in description of selected quasi-periodicities in cosmic ray time series which are of potential use for space weather studies, (ii) status in the forecast of geoeffective and radiation storm alerts using signatures of ground-based observations, (iii) problem of relativistic electrons in the vicinity of Earth.

The Electron Proton Helium INstrument as an example for a Space Weather Radiation Instrument

Patrick **Kühl**, Bernd Heber, Raúl Gómez-Herrero, Olga Malandraki, Arik Posner and Holger Sierks

J. Space Weather Space Clim. **2020**, 10, 53

https://www.swsc-journal.org/articles/swsc/pdf/2020/01/swsc200043.pdf

The near-Earth energetic particle environment has been monitored since the 1970's. With the increasing importance of quantifying the radiation risk for, e.g. for the human exploration of the Moon and Mars, it is essential to continue and further improve these measurements. The Electron Proton Helium INstrument (EPHIN) on-board SOHO continually provides these data sets to the solar science and space weather communities since 1995. Here, we introduce the numerous data products developed over the years and present space weather related applications. Important design features that have led to EPHINs success as well as lessons learned and possible improvements to the instrument are also discussed with respect to the next generation of particle detectors.

Soon to Unveil Space Weather Services,

Kumar, M.

(**2010**), ESA Space Weather, 8, S10005, doi:10.1029/2010SW000623.

The European Space Agency (ESA) will soon begin services associated with its new Space Situational Awareness (SSA) Preparatory Programme, authorized by ESA in November 2008. With a management team based at ESA's European Space Astronomy Centre (ESAC), in Spain, the program will enable scientists, government officials, and industry representatives to better utilize and access space technology by providing real-time information on the near-Earth space environment and its hazards. These hazards involve possible collisions between orbiting objects in space, potential meteor and asteroid strikes, and harmful space weather. This latter aspect, covered under SSA's Space Weather (SWE) element, will begin with the establishment of initial services in October 2010.

Facility Will Help Transition Models Into Operations

Mohi **Kumar**

SPACE WEATHER, VOL. 7, S02001, doi:10.1029/2009SW000471, **2009**

The U.S. National Oceanic and Atmospheric Administration's Space Weather Prediction Center (NOAA SWPC), in partnership with the U.S. Air Force Weather Agency (AFWA), is establishing a center to promote and facilitate the transition of space weather models to operations. The new facility, called the Developmental Testbed Center (DTC), will take models used by researchers and rigorously test them to see if they can withstand continued use as viable warning systems. If a model used in a space weather warning system crashes or fails to perform well, severe consequences can result. These include increased radiation risks to astronauts and people traveling on high-altitude flights, national security vulnerabilities from the loss of military satellite communications, and the cost of replacing damaged military and commercial spacecraft.

NOAA Improves Space Weather Watch Products,
Kunches, J., and R. Viereck
(**2012**), Space Weather, 10, S08007,
Recognizing that space weather events are now being closely monitored by governments and industries as well as by space weather scientists, NOAA's Space Weather Prediction Center (SWPC) is changing the way it characterizes geomagnetic storm activity.
To improve its customer support, SWPC is moving away from the use of the A index, instead using the more straightforward G scale for warnings of geomagnetic activity.
The list of watch products at http://www.swpc.noaa.gov/alerts/AlertsTable.html
NOAA Space Weather Scales are available at http://www.swpc.noaa.gov/NOAAscales/

PSTEP: project for solar-terrestrial environment prediction
Kusano, Kanya ; Ichimoto, Kiyoshi ; Ishii, Mamoru ; Miyoshi, Yoshizumi ; Yoden, Shigeo ; et al.
Earth, Planets and Space, Volume 73, Issue 1, article id.159, **2021**
https://earth-planets-space.springeropen.com/track/pdf/10.1186/s40623-021-01486-1.pdf
https://doi.org/10.1186/s40623-021-01486-1
Although solar activity may significantly impact the global environment and socioeconomic systems, the mechanisms for solar eruptions and the subsequent processes have not yet been fully understood. Thus, modern society supported by advanced information systems is at risk from severe space weather disturbances. Project for solar-terrestrial environment prediction (PSTEP) was launched to improve this situation through synergy between basic science research and operational forecast. The PSTEP is a nationwide research collaboration in Japan and was conducted from April 2015 to March 2020, supported by a Grant-in-Aid for Scientific Research on Innovative Areas from the Ministry of Education, Culture, Sports, Science and Technology of Japan. By this project, we sought to answer the fundamental questions concerning the solar-terrestrial environment and aimed to build a next-generation space weather forecast system to prepare for severe space weather disasters. The PSTEP consists of four research groups and proposal-based research units. It has made a significant progress in space weather research and operational forecasts, publishing over 500 refereed journal papers and organizing four international symposiums, various workshops and seminars, and summer school for graduate students at Rikubetsu in 2017. This paper is a summary report of the PSTEP and describes the major research achievements it produced. **21 May 2016, 6 Sep 2017**

COSPAR Panel on Space Weather: En Route to a Global Space Weather Forum—Establishing the Coordinated Research Initiative Targeting the Improvements of Space Weather Operational Services
Maria **Kuznetsova**
Space Research Today
Volume 201, April **2018**, Pages 7-14
https://reader.elsevier.com/reader/sd/A6C46BBE3E4DFCA2A03B0FA7E58B54D18541E2618245AFC3B7555E5DA68AE887E05A0571B2A6512B203F34090815E96A
https://www.sciencedirect.com/science/article/pii/S175292981830029X?via%3Dihub

Validating the Space Weather Modeling Framework (SWMF) for applications in northern Europe
Ground magnetic perturbation validation
Norah Kaggwa **Kwagala**1*, Michael Hesse1,3, Therese Moretto1, Paul Tenfjord1, Cecilia Norgren1, Gabor Tóth2, Tamas Gombosi2, Håkon M. Kolstø1 and Susanne F. Spinnang
J. Space Weather Space Clim. **2020**, 10, 33
https://www.swsc-journal.org/articles/swsc/pdf/2020/01/swsc200011.pdf
In this study we investigate the performance of the University of Michigan's Space Weather Modeling Framework (SWMF) in prediction of ground magnetic perturbations (ΔB) and their rate of change with time (dB/dt), which is

directly connected to geomagnetically induced currents (GICs). We use the SWMF set-up where the global magnetosphere provided by the Block Adaptive Tree Solar-wind Roe-type Upwind Scheme (BATS-R-US) MHD code, is coupled to the inner magnetosphere and the ionospheric electrodynamics. The validation is done for ΔB and dB/dt separately. The performance is evaluated via data-model comparison through a metrics-based approach. For ΔB, the normalized root mean square error (nRMS) and the correlation coefficient are used. For dB/dt, the probability of detection, the probability of false detection, the Heidke skill score, and the frequency bias are used for different dB/dt thresholds. The performance is evaluated for eleven ground magnetometer stations located between 59° and 85° magnetic latitude and spanning about five magnetic local times. Eight geomagnetic storms are studied. Our results show that the SWMF predicts the northward component of the perturbations better at lower latitudes (59°–67°) than at higher latitudes (>67°), whereas for the eastward component, the model performs better at high latitudes. Generally, the SWMF performs well in the prediction of dB/dt for a 0.3 nT/s threshold, with a high probability of detection ≈0.8, low probability of false detection (<0.4), and Heidke skill score above zero. To a large extent the model tends to predict events as often as they are actually occurring in nature (frequency bias 1). With respect to the metrics measures, the dB/dt prediction performance generally decreases as the threshold is raised, except for the probability of false detection, which improves.

Near realtime forecasting of MeV protons on the basis of sub relativistic electrons

Labrenz, Johannes; Heber, Bernd; Kuehl, Patrick; Sarlanis, Christos; Malandraki, Olga; Posner, Arik
EGU General Assembly 2016, held 17-22 April, 2016 in Vienna Austria, p.8076

A major impact on human and robotic space exploration activities is the sudden and prompt occurrence of solar energetic ion events. In order to provide up to an hour warning before these particles arrive at Earth, relativistic electron and below 50 MeV proton data from the Electron Proton Helium Instrument (EPHIN) on SOHO were used to implement the 'Relativistic Electron Alert System for Exploration (REleASE)'. It has been demonstrated that the analysis of relativistic electron time profiles provides a low miss and false alarm rate. High Energy Solar Particle Events foRecastIng and Analysis (HESPERIA) is a project funded within the European Union's Horizon 2020 research and innovation programme (PROTEC-1-2014 Call: Space Weather). Within this project the REleASE forecasting scheme was rewritten in the open access programming language PYTHON and will be made public. As a next step, we have analyzed the possibility to also use, along with relativistic electrons (v > 0.9 c) provided by SOHO, near-relativistic (v <0.8 c) electron measurements from other instruments like the Electron Proton Alpha Monitor (EPAM) aboard the Advanced Composition Explorer (ACE). This would prove to be particularly useful during periods that SOHO does not provide continuous near real-time data. We show that the ACE/EPAM observations can be adapted to the REleASE forecasting scheme to provide reliable SEP forecasts. A comparison of measured and forecast proton intensities by SOHO/EPHIN and ACE/EPAM will be presented. In addition we investigated the false alarm rate and detection probability of solar ion events. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 637324.

Improving solar wind forecasting using Data Assimilation

Matthew **Lang**, Jake Witherington, Harriet Turner, Matt Owens, Pete Riley
Space Weather **Volume19, Issue7** e2020SW002698 **2021**
https://arxiv.org/pdf/2012.06362.pdf
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020SW002698

Data Assimilation (DA) has enabled huge improvements in the skill of terrestrial operational weather forecasting. In this study, we use a variational DA scheme with a computationally efficient solar wind model and in situ observations from STEREO A, STEREO B and ACE. This scheme enables solar-wind observations far from the Sun, such as at 1 AU, to update and improve the inner boundary conditions of the solar wind model (at 30 solar radii). In this way, observational information can be used to improve estimates of the near-Earth solar wind, even when the observations are not directly downstream of the Earth. This allows improved initial conditions of the solar wind to be passed into forecasting models. To this effect we employ the HUXt solar wind model to produce 27-day forecasts of the solar wind during the operational time of STEREO B (01/11/2007−30/09/2014). At ACE, we compare these DA forecasts to the corotation of STEREO B observations and find that 27-day RMSE for STEREO-B corotation and DA forecasts are comparable. However, the DA forecast is shown to improve solar wind forecasts when STEREO-B's latitude is offset from Earth. And the DA scheme enables the representation of the solar wind in the whole model domain between the Sun and the Earth to be improved, which will enable improved forecasting of CME arrival time and speed.

Highlights of the "Space Weather Risks and Society" Workshop

Langhoff, Stephanie R.; Straume, Tore
Space Weather, Vol. 10, No. 0, S06004, **2012**
http://dx.doi.org/10.1029/2012SW000792

An interdisciplinary and international group of subject matter experts and societal stakeholders came together on 15-16 October 2011 to participate in the Space Weather Risks and Society workshop held at the NASA Ames Research Center (ARC). Talks focus on the space weather threats and how to address them.

Chapter 7 - Supergeomagnetic Storms: Past, Present, and Future **Review**

Gurbax S.**Lakhina** Bruce T.Tsurutani

In: Extreme Events in Geospace Origins, Predictability, and Consequences

2018, Pages 157-185 **File**

http://sci-hub.tw/10.1016/B978-0-12-812700-1.00007-8

Geomagnetic storms are large-scale disturbances in the Earth's magnetic field due to orders of magnitude increases in trapped energetic ~ 10–300 keV particle fluxes in the magnetosphere. During geomagnetic storms, the horizontal component of the low-latitude magnetic fields is significantly depressed over a time span of one to a few hours from the diamagnetic effect from the enhanced ring current fluxes. This is known as the main phase of the storm, and is followed by the recovery phase where the particles are lost. This latter phase may extend over several days. The strength of magnetic storms is measured by the Disturbance Storm Time (Dst) index. Superintense magnetic storms (defined here as those with Dst < − 500 nT), although relatively rare in occurrence, have the largest societal and technological impacts. Such storms can cause life-threatening power outages, satellite damage, satellite communication failures, navigational problems, and loss of satellites in low Earth orbit (LEO). In this chapter, we shall first review the present knowledge about supermagnetic storms. Then, we discuss the superstorms that have occurred in the past, and consider the case history of the Carrington storm as a representative example. This will be followed by the consideration of supermagnetic storms of present (the space-age era). Next, we explore supermagnetic storms that can occur in the future with an emphasis on the maximum possible intensity of an event. The occurrence probability of superstorms having intensities equal to the Carrington storm or higher will be discussed. Finally, we discuss the status of nowcasting (~ 1 h) and short-time scale forecasting (~ a few hours to a few days) of supermagnetic storms. **September 1–2, 1859, March 13–16, 1989**

Table 1 A List of Intense and Superintense Magnetic Storms From Colaba and Alibag Magnetic Observatories (1847-2005)

International Geophysical Year: Space Weather Impacts in February 1958

Louis J. **Lanzerotti** , Daniel N. Baker

Space Weather Volume16, Issue7 July **2018** Pages 775-776

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2018SW001839

Sixty years ago the large February 1958 geomagnetic storm in the International Geophysical Year produced significant impacts on the electrical technologies of the day. The impacts of this major storm had considerable public exposure and interest. In the six decades since the large International Geophysical Year storm, the technology elements impacted during that storm—communications and power systems—continue to be employed, sometimes in new ways. Importantly, over the decades new human technologies that can be impacted by space weather processes have been invented and implemented. Continued progress is required in the research and understanding of space processes so as to design for, mitigate against, and operate through severe geomagnetic disturbances.

Space Weather: Historical and Contemporary Perspectives **Review**

Louis J. **Lanzerotti**

Space Science Reviews **2017**

https://link.springer.com/content/pdf/10.1007%2Fs11214-017-0408-y.pdf

A somewhat personalized overview is presented of the effects of solar-terrestrial processes on electrical technologies, beginning with the electrical telegraphs in the mid-eighteenth century to the current era of extensive ground- and space-based commercial and governmental technical systems (including national security) upon which modern society depends. As human technologies increased in diversity over the last century and a half, space weather effects have continued to be of significant importance in the successful design and operations of many of these technologies.

Space weather research: Earth's radiation belts **Review**

Louis J. **Lanzerotti**, Daniel N. Baker

Volume 15, Issue 6 June **2017** Pages 742–745

http://onlinelibrary.wiley.com/doi/10.1002/2017SW001654/full

http://onlinelibrary.wiley.com.sci-hub.cc/doi/10.1002/2017SW001654/abstract;jsessionid=4A82E36E86E7905A86D86E554734B025.f03t02

Fundamental research on Earth's space radiation environment is essential for the design and the operations of modern technologies—for communications, weather, navigation, and national security—that fly in the hostile space weather conditions above Earth's atmosphere. As the technologies become ever more advanced, more sophisticated understanding—and even predictability—of the environment is required for mission success.

Space Weather Strategy and Action Plan: The National Program Is Rolled Out
Louis J. **Lanzerotti**
Space Weather   Volume 13, Issue 12   December **2015** Pages 824–825
http://onlinelibrary.wiley.com/doi/10.1002/2015SW001334/full

Interview With Dr. Thomas Berger (the Director of NOAA's Space Weather Prediction Center (SWPC) in Boulder)
Lanzerotti, L. J. (**2014**), , NOAA, *Space Weather*, *12*,
Space Weather Quarterly, Volume 11, Issue 4, Article first published online: 4 DEC **2014**
http://onlinelibrary.wiley.com/doi/10.1002/SWQv11i004/pdf

Earth Observations and Space Weather
Louis J. **Lanzerotti**
Space Weather, Volume 12, Issue 8, page 527, August **2014**
http://onlinelibrary.wiley.com/doi/10.1002/SWQv11i003/pdf

Space Weather Effects in a Reduced Solar Cycle
Louis J. **Lanzerotti**
Volume 12, Issue 5, page 299, May **2014**
http://onlinelibrary.wiley.com/doi/10.1002/SWQv11i001/pdf

Space Weather Research and Policy for This Decade
Lanzerotti, Louis J.
Space Weather, Vol. 10, No. 11, S11008, **2012**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2012SW000875
The latest decadal survey focuses on the importance of understanding the solar-terrestrial environment for societal needs
See http://www.nap.edu/catalog.php?record_id=13060

Space Weather and Earth Electrical Currents
Lanzerotti, Louis J.
Space Weather, Vol. 10, No. 0, S05009, **2012**
http://dx.doi.org/10.1029/2012SW000814
Geomagnetic activity presents challenges to electrical power systems.
Several policy-oriented activities have recently occurred that have been targeted specifically to the issue of electric grid reliability and GICs. These activities have been concerned largely with events that could potentially catastrophically disrupt grid systems for lengthy intervals. Such activities include a November 2011 report from the JASON group (http://www.fas.org/irp/agency/dod/jason/spaceweather.pdf), an April 2012 Staff Technical Conference at the Federal Energy Regulatory Commission (https://www.federalregister.gov/articles/2012/04/26/2012-10063/staff-technical-conference-on-geomagnetic-disturbances-to-the-bulk-power-system-technical-conference), and the third Electric Infrastructure Security Summit held in mid-May 2012 in London (http://www.eissummit.com/agenda.asp).
See http://www.sdr.gov/docs/185820_Space_FINAL.pdf

Space Weather and Natural Hazards
Lanzerotti, Louis J.
Space Weather, Vol. 10, No. 0, S05008, **2012**
http://dx.doi.org/10.1029/2012SW000810
Solar and terrestrial space environments' effects on current-day technical systems was topic at AGU forum

Government and Public Awareness of Space Weather

Lanzerotti, Louis J.

Space Weather, Vol. 9, No. 7, S07008, **2011**

Solar cycle 24 continues to provide confusion in its start and its unsteady rise toward an uncertain maximum. Nevertheless, many entities, including the popular press and influential government agencies, are becoming more aware of the effects of the Sun and the near-Earth space environment on essential modern-day technologies. Within the past 6 months, news articles in the printed and digital press have included such headlines as "Solar storm delivers glancing blow to Earth—and a warning" (Christian Science Monitor, 9 June 2011), "Magnetic north pole shifts, forces runway closures at Florida airport" (FoxNews.com, 6 January 2011), "Major solar flare erupts, may make auroras visible in northern U.S." (SPACE.com, 10 March 2011, but picked up by FoxNews.com and Yahoo News), and "As the sun awakens, the power grid stands vulnerable" (Washington Post, 20 June 2011). All such news stories for the general public are a welcome recognition that weather in space can have important implications for human activities, including the performance—and even survivability—of some technologies.

Research to Operations Paired With Operations to Research,

Lanzerotti, L. J.

(**2011**), Space Weather, 9, S02003,

Solar-terrestrial research is important to many practical problems facing numerous technologies on, and flying above, Earth. The new decadal survey of solar and space physics (see http://sites.nationalacademies.org/SSB/CurrentProjects/SSB_056864 and Lanzerotti [2010]) recognizes this and has established an active working group, "Research to Operations/Operations to Research" (R2O/O2R). The establishment of this working group is a significant advancement over the more ad hoc treatment of R2O/O2R issues in the first decadal survey, in 2002. The O2R portion of the responsibilities of the R2O/O2R working group is critical for the new decadal survey. The incorporation of O2R (in addition to the more conventional and prevalent embrace by the research community of R2O) clearly acknowledges that requirements from the "operations" community—designers, systems operators, modelers, forecasters—will be seriously incorporated into the thinking and discussions by the decadal survey steering committee for new solar-terrestrial research programs, initiatives, and activities.

Contrasting Large Solar Events,

Lanzerotti, L. J.

(**2010**), Space Weather, 8, S10003, doi:10.1029/2010SW000624.

After an unusually long solar minimum, solar cycle 24 is slowly beginning. A large coronal mass ejection (CME) from sunspot 1092 occurred on 1 August 2010, with effects reaching Earth on 3 August and 4 August, nearly 38 years to the day after the huge solar event of 4 August 1972. The prior event, which those of us engaged in space research at the time remember well, recorded some of the highest intensities of solar particles and rapid changes of the geomagnetic field measured to date. What can we learn from the comparisons of these two events, other than their essentially coincident dates? One lesson I took away from reading press coverage and Web reports of the August 2010 event is that the scientific community and the press are much more aware than they were nearly 4 decades ago that solar events can wreak havoc on space-based technologies.

A New Decadal Survey

Lanzerotti , Louis J.

Space Weather, Vol. 8, No. 7, S07009, **2010**

Because of increased use of technologies that are vulnerable to disturbances in the solar-terrestrial system, better predictability of the Sun-Earth system and better infrastructure for operational models will likely be major goals of a new decadal survey of solar and space physics.

Space weather is expected to be an important part of the new decadal survey of solar and space physics, currently set for release in 2012. This is appropriate—ever more detailed knowledge, modeling, and predictability of the Sun-Earth system are required. Every 10 years, scientists in several different space-related research subjects (e.g., astronomy, solar and space physics, planetary and Earth sciences) convene to assess the progress of their field over the previous decade and to recommend research areas for the coming decade. Organized by the U.S. National Academies, these surveys set the tone for national priorities in a given subject.

The Need for Long-Term Solar-Terrestrial Data Series,

Lanzerotti, L. J.

Space Weather, 7, S05006, **2009**, doi:10.1029/2009SW000496.

Designing technical systems to operate successfully under space weather conditions requires accurate knowledge of the climatology of the solar- terrestrial environment. Unfortunately, there are too few long-term direct measurements of this environment. This often places engineers in a dilemma: either overdesign a system to compensate for extreme space weather occurrences—resulting in increased costs—or assume a more benign environment to lower costs—and thus likely increase system risk. Such a dilemma often faces designers of systems that are to operate in Earth's radiation belts, where current models, more than 3 decades old, were not constructed for climatological use.

A Good Start: Workshop Tackles Space Weather Economics

Louis J. **Lanzerotti**

SPACE WEATHER, VOL. 6, S07004, doi:10.1029/2008SW000416, **2008**

http://dx.doi.org/10.1029/2008SW000416

As I wrote earlier this year, reliable estimates of the economic impacts of a space weather event on technologies have often been seriously lacking (see L. Lanzerotti, *Space Weather*, *6*, S01002, doi:10.1029/2007SW000385, 2008). However, I am happy to note that the Space Studies Board of the U.S. National Research Council took an important step toward setting a framework for achieving some of these “reliable estimates” in a workshop that was held in late May in Washington, D. C. The meeting drew active participation from the academic research community and major government agencies in the National Space Weather Program (http://www.nswp.gov), as well as a significant number of commercial interests large and small. These latter included enterprises that use space weather information for design decisions and/or successful operations, as well as vendors of space weather products and services.

Estimation of the solar flare neutron worst-case fluxes and fluences for missions traveling close to the Sun

D. **Lario**

Space Weather, Vol. 10, No. 3, S03002, **2012**

http://dx.doi.org/10.1029/2011SW000732

A method to estimate the total fluence of solar flare neutrons at a spacecraft traveling in the innermost part of the heliosphere (at heliocentric radial distances of <1 AU) is presented. The results of the neutron production and emissivity codes of Hua and Lingenfelter (1987a, 1987b) scaled to one of the largest solar neutron events ever observed at the Earth are used to derive a conservative estimate of the energy spectrum of neutrons emitted from the Sun after a large solar flare. By taking into account the survival probability of a neutron to reach a certain heliocentric distance, we evaluate the observed time-integrated spectrum of solar neutrons as a function of the heliocentric distance of the observer. By considering (1) a working relationship between the soft X-ray class of a flare and the flare's production of solar neutrons, and (2) the number and size of soft X-ray flares that may occur during a mission traveling close to the Sun, we compute an upper limit for the total fluence of solar neutrons at energies >1 MeV, >10 MeV, >100 MeV and >1000 MeV to which such a mission may be exposed. We apply this method to the Solar Probe Plus mission. Although our method gives a conservative estimate of neutron fluxes, the predicted mission-integrated fluence of solar neutrons at Solar Probe Plus is orders of magnitude below that of solar energetic protons.

Estimation of solar energetic proton mission-integrated fluences and peak intensities for missions traveling close to the Sun

Lario, D.; Decker, R. B.

Space Weather, Vol. 9, No. 11, S11003, **2011**

http://dx.doi.org/10.1029/2011SW000708

A method to estimate both solar energetic particle mission-integrated fluences and solar energetic particle peak intensities for missions traveling through the innermost part of the heliosphere (r < 1 AU) is presented. By using (1) an extensive data set of particle intensities measured at 1 AU over the last three solar cycles, (2) successive launch dates for the mission traveling close to the Sun over the time interval spanned by our data set, and (3) appropriate radial dependences to extrapolate fluences and peak intensities measured at 1 AU to the heliocentric radial distance of the mission at each specific time, we generate distributions of both mission-integrated fluences and maximum peak intensities. From these distributions we extract the values of mission-integrated fluence and maximum peak intensity at a required confidence level. Results of this method applied to the specific case of the nominal prime mission of Solar Probe Plus are shown.

Relationship Between NM Data and Radiation Dose at Aviation Altitudes During GLE Events

N. Larsen, A. Mishev

Space Weather   Volume22, Issue6 June **2024** e2024SW003885

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2024SW003885

https://doi.org/10.1029/2024SW003885
Ground-level enhancements (GLEs) are sporadic events that signal the arrival of high fluxes of solar energetic particles (SEPs) that have been produced by solar eruptions. Ground-level enhancement events are characterized by a significant increase in the count rate of ground-based neutron monitors (NMs). The arrival of high-energy SEPs in the atmosphere leads to an enhancement of the radiation environment, with the enhancement at aviation altitudes being particularly hazardous to human health as pilots, crew, and airline passengers can be subjected to dangerous levels of radiation during a GLE. Through the use of a currently expanding library of analyzed GLEs and the application of a newly developed atmospheric radiation model, both of which have been created in-house, we found a strong statistically significant relationship between real-time NM data during GLE events and the radiation doses at aviation altitudes. This result provides a strong scientific basis for the use of real-time NM data as a proxy for radiation dose estimates during GLE events and aids in the development of future nowcasting models to help mitigate the dangerous impacts of future GLEs.
Table 1List of Used Ground-Level Enhancements That Have Been Analyzed

Predicting Solar Flares with Remote Sensing and Machine Learning

Erik **Larsen**

2021

https://arxiv.org/ftp/arxiv/papers/2110/2110.07658.pdf
High energy solar flares and coronal mass ejections have the potential to destroy Earth's ground and satellite infrastructures, causing trillions of dollars in damage and mass human suffering. Destruction of these critical systems would disable power grids and satellites, crippling communications and transportation. This would lead to food shortages and an inability to respond to emergencies. A solution to this impending problem is proposed herein using satellites in solar orbit that continuously monitor the Sun, use artificial intelligence and machine learning to calculate the probability of massive solar explosions from this sensed data, and then signal defense mechanisms that will mitigate the threat. With modern technology there may be only safeguards that can be implemented with enough warning, which is why the best algorithm must be identified and continuously trained with existing and new data to maximize true positive rates while minimizing false negatives. This paper conducts a survey of current machine learning models using open source solar flare prediction data. The rise of edge computing allows machine learning hardware to be placed on the same satellites as the sensor arrays, saving critical time by not having to transmit remote sensing data across the vast distances of space. A system of systems approach will allow enough warning for safety measures to be put into place mitigating the risk of disaster.

A Short-term ESPERTA-based Forecast Tool for Moderate-to-extreme Solar Proton Events

M. **Laurenza**1, T. Alberti1,2, and E. W. Cliver3,4

2018 ApJ 857 107 **File**

http://sci-hub.tw/http://iopscience.iop.org/0004-637X/857/2/107/
The ESPERTA (Empirical model for Solar Proton Event Real Time Alert) forecast tool has a Probability of Detection (POD) of 63% for all >10 MeV events with proton peak intensity ≥10 pfu (i.e., ≥S1 events, S1 referring to minor storms on the NOAA Solar Radiation Storms scale), from 1995 to 2014 with a false alarm rate (FAR) of 38% and a median (minimum) warning time (WT) of ~4.8 (0.4) hr. The NOAA space weather scale includes four additional categories: moderate (S2), strong (S3), severe (S4), and extreme (S5). As S1 events have only minor impacts on HF radio propagation in the polar regions, the effective threshold for significant space radiation effects appears to be the S2 level (100 pfu), above which both biological and space operation impacts are observed along with increased effects on HF propagation in the polar regions. We modified the ESPERTA model to predict ≥S2 events and obtained a POD of 75% (41/55) and an FAR of 24% (13/54) for the 1995–2014 interval with a median (minimum) WT of ~1.7 (0.2) hr based on predictions made at the time of the S1 threshold crossing. The improved performance of ESPERTA for ≥S2 events is a reflection of the big flare syndrome, which postulates that the measures of the various manifestations of eruptive solar flares increase as one considers increasingly larger events.
Table 2 …100 pfu SPE Flare List (1995–2014)

Хорошее Введение

A technique for short-term warning of solar energetic particle events based on flare location, flare size, and evidence of particle escape

M. **Laurenza**, E. W. Cliver, J. Hewitt, M. Storini, A. G. Ling, C. C. Balch, M. L. Kaiser

Space Weather, 7, S04008, doi:10.1029/2007SW000379. **2009**

We have developed a technique to provide short‐term warnings of solar energetic proton (SEP) events that meet or exceed the Space Weather Prediction Center threshold of J (>10 MeV) = 10 pr cm^{-2} s^{-1} sr^{-1}. The method is based on flare location, flare size, and evidence of particle acceleration/escape as parameterized by flare longitude, time‐integrated soft X‐ray intensity, and time‐integrated intensity of type III radio emission at ~1 MHz, respectively. In this technique, warnings are issued 10 min after the maximum of ≥M2 soft X‐ray flares. For the solar cycle 23 (1995–2005) data on which it was developed, the method has a probability of detection of 63% (47/75), a false alarm rate of 42% (34/81), and a median warning time of ~55 min for the 19 events successfully predicted by our technique for which SEP event onset times were provided by Posner (2007). These measures meet or exceed verification results for competing automated SEP warning techniques but, at the present stage of space weather forecasting, fall well short of those achieved with a human (aided by techniques such as ours) making the ultimate yes/no SEP event prediction. We give some suggestions as to how our method could be improved and provide our flare and SEP event database in the auxiliary material to facilitate quantitative comparisons with techniques developed in the future.

A small mission concept to the Sun-Earth Lagrangian L5 point for innovative solar, heliospheric and space weather science

Lavraud, B.; Liu, Y.; Segura, K.; He, J.; Qin, G.; Temmer, M. …

Journal of Atmospheric and Solar-Terrestrial Physics, Volume 146, p. 171-185, **2016**

http://www.sciencedirect.com/science/article/pii/S1364682616301456

We present a concept for a small mission to the Sun-Earth Lagrangian L5 point for innovative solar, heliospheric and space weather science. The proposed INvestigation of Solar-Terrestrial Activity aNd Transients (INSTANT) mission is designed to identify how solar coronal magnetic fields drive eruptions, mass transport and particle acceleration that impact the Earth and the heliosphere. INSTANT is the first mission designed to (1) obtain measurements of coronal magnetic fields from space and (2) determine coronal mass ejection (CME) kinematics with unparalleled accuracy. Thanks to innovative instrumentation at a vantage point that provides the most suitable perspective view of the Sun-Earth system, INSTANT would uniquely track the whole chain of fundamental processes driving space weather at Earth. We present the science requirements, payload and mission profile that fulfill ambitious science objectives within small mission programmatic boundary conditions.

Dst index forecast based on ground-level data aided by bio-inspired algorithms

J. A. **Lazzús** , P. Vega-Jorquera , L. Palma-Chilla , M. V. Stepanova, N. V. Romanova

Space Weather **2019**

https://doi.org/10.1029/2019SW002215

In this study, different hybridized techniques that combine an artificial neural network (ANN) with bio-inspired optimization algorithms such as particle swarm optimization (PSO), genetic algorithm (GA), and a hybridized PSO+GA were applied to update the ANN connection weights and so forecast the disturbance storm time (Dst) index. The past values of Dst index time series were used as input parameters to forecast its variation from 1 to 6 hours ahead. The database collected considers 233,760 hourly data from 01 January 1990 to 31 August 2016, containing storms and quiet period, grouped into three data sets: learning set (116,880 hourly data points), validation set (58,440 data points), and testing set (58,440 data points). Several ANN configurations were studied and optimized during the training process by evaluating the root mean square error (RMSE) and the correlation coefficient (R). An analysis of the predictive capability of each method was made year per year, and according to the levels of the geomagnetic storm. Also, an additional test was applied to the proposed method using 17 intense geomagnetic storms reported during solar cycle 24, including the St. Patrick's Day storm of 2015. Results show that the hybridized ANN+PSO method can forecast the Dst index quite accurately from 1 to 3 h in advance (with RMSE≤5 nT and R≥0.9), while the ANN+PSO+GA method can forecast the Dst index quite accurately from 4 to 6 h ahead (RMSE≤7 nT and R≥0.8)

Forecasting the Dst index using a swarm-optimized neural network

J. A. **Lazzús**, P. Vega, P. Rojas, I. Salfate

Space Weather Volume 15, Issue 8 August **2017** Pages 1068–1089

http://sci-hub.cc/10.1002/2017SW001608

A hybrid technique that combines an artificial neural network with a particle swarm optimization (ANN+PSO) was used to forecast the disturbance storm time (Dst) index from 1 to 6 h ahead. Our ANN was optimized by PSO to update ANN weights and to predict the short-term Dst index using past values as input parameters. The database used contains 233,760 hourly data from 1 January 1990 to 31 August 2016, considering storms and quiet period, grouped into three data sets: learning set (with 116,880 hourly data points), validation set (with 58,440 data points), and testing set (with 58,440 data points). Several ANN topologies were studied, and the best architecture was determined by systematically adding neurons and evaluating the root-mean-square error (RMSE) and the correlation coefficient (R) during the training process. These results show that the hybrid algorithm is a powerful technique for forecasting the Dst index a short time in advance like t + 1 to t + 3, with RMSE from 3.5 nT to 7.5 nT, and R from 0.98 to 0.90. However, t + 4 to t + 6 predictions become slightly more uncertain, with RMSE from 8.8 nT to 10.9 nT, and R from 0.86 to 0.79. Additionally, an exhaustive analysis according to geomagnetic storm magnitude was conducted. In general, the results show that our hybrid algorithm can be correctly trained to forecast the Dst index with appropriate precision and that Dst past behavior significantly affects adequate training and predicting capabilities of the implemented ANN.

Extreme space weather events caused by super active regions during solar cycles 21-24

Gui-Ming **Le**, Gui-Ang Liu, Ming-Xian Zhao, Tian Mao, Ping-Guo Xu

Research in Astronomy and Astrophysics **2021**

https://arxiv.org/pdf/2103.00670.pdf **File**

Extreme space weather events including ≥X5.0 flares, ground level enhancement (GLE) events and super geomagnetic storms (Dst ≤ -250 nT) caused by super active regions (SARs) during solar cycles 21-24 were studied. The total number of ≥X5.0 solar flares was 62, 41 of them were X5.0-X9.9 flares and 21 of them were ≥X10.0 flares. We found that 83.9\% of the ≥X5.0 flares were produced by SARs. 78.05\% of the X5.0-X9.9 and 95.24\% of the ≥X10.0 solar flares were produced by SARs. 46 GLEs registered during solar cycles 21-24, and 25 GLEs were caused by SARs, indicating that 54.3\% of the GLEs were caused by SARs. 24 super geomagnetic storms were recorded during solar cycles 21-24, and 12 of them were caused by SARs, namely 50\% of the super geomagnetic storms are caused by SARs. It is found that only 29 SARs can produce ≥X5.0 flares, 15 SARs can produce GLEs and 10 SARs can produce super geomagnetic storms. Of the 51 SARs, only 33 SARs can produce at least one extreme space weather event, while none of the rest 18 SARs can produce an extreme space weather event. There were only 4 SARs, each of them can produce not only a ≥X5.0 flare, but also a GLE event and a super geomagnetic storm. Most of the extreme space weather events caused by the SARs appeared during solar cycles 22 and 23, especially for GLE events and super geomagnetic storms. The longitudinal distributions of source locations for the extreme space weather events caused by SARs were also studied. **28-30, October 2003**

Table 1: The flares with intensities ≥X5.0 caused by SARs during solar cycles 21-24.

Table 2: The GLE events caused by SARs during solar cycles 21-24.

Table 3: The SGSs and the related ARs during solar cycles 21-24.

Termination of Solar Cycles and Correlated Tropospheric Variability

Robert J **Leamon**, Scott W. McIntosh, Daniel R. Marsh

JGR **2018**

https://arxiv.org/pdf/1812.02692.pdf

The Sun provides the energy required to sustain life on Earth and drive our planet's atmospheric circulation. However, establishing a solid physical connection between solar and tropospheric variability has posed a considerable challenge across the spectrum of Earth-system science. The canon of solar variability, the solar fiducial clock, lies almost exclusively with the 400 years of human telescopic observations that demonstrates the waxing and waning number of sunspots, over an 11(ish) year period. Recent research has demonstrated the critical importance of the underlying 22-year magnetic polarity cycle in establishing the shorter sunspot cycle. Integral to the manifestation of the latter is the spatio-temporal overlapping and migration of oppositely polarized magnetic bands. The points when these bands emerge at high solar latitudes and cancel at the equator are separated by almost 20 years. Here we demonstrate the impact of these `termination' points on the Sun's radiative output and particulate shielding of our atmosphere through the dramatically rapid reconfiguration of solar magnetism. These events reset the Sun's fiducial clock and present a new portal to explore the Sun-Earth connection. Using direct observation and proxies of solar activity going back six decades we can, with high statistical significance, demonstrate an apparent correlation between the solar cycle terminations and the largest swings of Earths oceanic indices--a previously overlooked correspondence. Forecasting the Sun's global behavior places the next solar termination in early 2020 and we thus anticipate a strong El Niño in 2019, and a strong La Niña in 2020; should such a major oceanic swing follow, our challenge becomes: when does correlation become causation and how does the process work?

On the Effect of the Interplanetary Medium on Nanodust Observations by the Solar Terrestrial Relations Observatory

G. **Le Chat**, K. Issautier, A. Zaslavsky, F. Pantellini, N. Meyer-Vernet, S. Belheouane, M. Maksimovic

Solar Phys. Volume 290, Issue 3, pp 933-942 **2015**

http://arxiv.org/pdf/1501.02632v1.pdf

Dust particles provide an important part of the matter composing the interplanetary medium; their mass flux at 1 AU is similar to that of the solar wind. http://arxiv.org/pdf/1501.02632v1.pdfThe high-velocity impact of a dust particle generates a small crater on the spacecraft: the dust particle and the crater material are vaporized. This produces a plasma cloud whose associated electrical charge induces an electric pulse measured with radio and plasma instruments. Since their first detection in the interplanetary medium, nanodust particles have been routinely measured using the Solar Terrestrial Relations Observatory/WAVES experiment [S/WAVES]. We present the nanodust properties measured using S/WAVES/Low Frequency Receiver [LFR] observations between 2007 and

2013, and for the first time present evidence of coronal mass ejection interaction with the nanodust, leading to a higher nanodust flux measured at 1 AU. Finally, possible influences of the inner planets on the nanodust flux are presented and discussed.

How open data and interdisciplinary collaboration improve our understanding of space weather: A risk and resiliency perspective. Review

Ledvina VE, Palmerio E, McGranaghan RM, Halford AJ, +++
Front. Astron. Space Sci. 9: 1067571. **2022**
doi: 10.3389/fspas.2022.1067571
https://www.frontiersin.org/articles/10.3389/fspas.2022.1067571/pdf

Space weather refers to conditions around a star, like our Sun, and its interplanetary space that may affect space- and ground-based assets as well as human life. Space weather can manifest as many different phenomena, often simultaneously, and can create complex and sometimes dangerous conditions. The study of space weather is inherently trans-disciplinary, including subfields of solar, magnetospheric, ionospheric, and atmospheric research communities, but benefiting from collaborations with policymakers, industry, astrophysics, software engineering, and many more. Effective communication is required between scientists, the end-user community, and government organizations to ensure that we are prepared for any adverse space weather effects. With the rapid growth of the field in recent years, the upcoming Solar Cycle 25 maximum, and the evolution of research-ready technologies, we believe that space weather deserves a reexamination in terms of a "risk and resiliency" framework. By utilizing open data science, cross-disciplinary collaborations, information systems, and citizen science, we can forge stronger partnerships between science and industry and improve our readiness as a society to mitigate space weather impacts. The objective of this manuscript is to raise awareness of these concepts as we approach a solar maximum that coincides with an increasingly technology-dependent society, and introduce a unique way of approaching space weather through the lens of a risk and resiliency framework that can be used to further assess areas of improvement in the field.

Heliophysics and Space Weather Science at ~1.5 AU: Knowledge Gaps and Need for Space Weather Monitors at Mars

Christina **Lee**, Beatriz Sánchez-Cano, Gina DiBraccio, Majd Mayyasi, Shaosui Xu, et al.
Front. Astron. Space Sci. 10: 1064208 **2023**
https://www.frontiersin.org/articles/10.3389/fspas.2023.1064208/pdf

This perspective article discusses the knowledge gaps and open questions regarding the solar and interplanetary drivers of space weather conditions experienced at Mars during active and quiescent solar periods, and the need for continuous, routine observations to address them. For both advancing science and as part of the strategic planning for human exploration at Mars by the late 2030s, now is the time to consider a network of upstream space weather monitors at Mars. Our main recommendations for the heliophysics community are the following: 1. Support the advancement for understanding heliophysics and space weather science at ∼1.5 AU and continue the support of planetary science payloads and missions that provide such measurements. 2. Prioritize an upstream Mars L1 monitor and/or areostationary orbiters for providing dedicated, continuous observations of solar activity and interplanetary conditions at ∼1.5 AU. 3. Establish new or support existing 1) joint efforts between federal agencies and their divisions and 2) international collaborations to carry out #1 and #2. **10 Sep 2017**

MAVEN observations of the solar cycle 24 space weather conditions at Mars.

Lee, C. O., Hara, T., Halekas, J. S., Thiemann, E., Chamberlin, P., Eparvier, F., … Jakosky, B. M. (**2017**). Journal of Geophysical Research: Space Physics. 122, 2768-2794
sci-hub.tw/10.1002/2016JA023495

The Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft has been continuously observing the variability of solar soft X-rays and EUV irradiance, monitoring the upstream solar wind and interplanetary magnetic field conditions and measuring the fluxes of solar energetic ions and electrons since its arrival to Mars. In this paper, we provide a comprehensive overview of the space weather events observed during the first ∼1.9 years of the science mission, which includes the description of the solar and heliospheric sources of the space weather activity. To illustrate the variety of upstream conditions observed, we characterize a subset of the event periods by describing the Sun-to-Mars details using observations from the MAVEN solar Extreme Ultraviolet Monitor, solar energetic particle (SEP) instrument, Solar Wind Ion Analyzer, and Magnetometer together with solar observations using near-Earth assets and numerical solar wind simulation results from the Wang-Sheeley-Arge-Enlil model for some global context of the event periods. The subset of events includes an extensive period of intense SEP electron particle fluxes triggered by a series of solar flares and coronal mass ejection (CME) activity in December 2014, the impact by a succession of interplanetary CMEs and their associated SEPs in March 2015, and the passage of a strong corotating interaction region (CIR) and arrival of the CIR shock-accelerated energetic particles in June 2015. However, in the context of the weaker heliospheric conditions observed throughout solar cycle 24, these events were moderate in comparison to the stronger storms observed previously at Mars.

Chapter 3 - Solar Flare Forecasting: Present Methods and Challenges **Review**

K.D.**Leka**, Graham Barnes

In: Extreme Events in Geospace Origins, Predictability, and Consequences **2018**, Pages 65-98

http://sci-hub.tw/10.1016/B978-0-12-812700-1.00003-0

Solar flares are one of the primary initiators of many space weather phenomena. Their fast initiation and orders-of-magnitude increase in high-energy electromagnetic radiation require true forecasting efforts. Today's probabilistic flare forecasting capability is arguably not very good. When faced with specific questions regarding timing and magnitude of impending flares in the context of a flare-productive sunspot group, short-range targeted predictions are beyond the present science's capabilities. Such shortcomings may be of most serious consequence in the context of extreme solar flares—situations where a catastrophic flare event is highly likely, but when it will occur is both unknown and of great importance. This situation points to the need for better identification of a unique physical parameter space in which solar flares occur, for identifying the relevant physical trigger (or triggers), for the ability to estimate the likelihood that a trigger's presence will produce an event, and what size an event is expected. **March 7, 2012**

The determination of satellite orbital decay from POD data during geomagnetic storms

Ruoxi **Li** , Jiuhou Lei

Space Weather **Volume19, Issue4** e2020SW002664 **2021**

https://doi.org/10.1029/2020SW002664

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020SW002664

In our previous study (Li et al., 2017), we derived the satellite energy-decay with a 20-minute resolution based on the Precise Orbit Determination (POD) data, using a proximate analytic approach to represent the time variation gravitational potential. In this follow-up study, we improved the previous approach and calculated the POD-based energy-decays by using a numerical integration approach. Based on the precise energy-decays, the orbital decays and decay rates with higher accuracy and resolution were further derived. The relative deviations of the orbital decays are generally less than 10% with respect to the accelerometer-reference. The satellite orbital decays and decay rates derived from this approach were used to study the effects of geomagnetic activities and background density on the orbital changes. Our results show that, during the severe November 2003 storm, the storm-induced orbital decay rate increased by a factor of 8 with respect to the quiet-time reference. This POD-based integration approach was also applied to study the orbital changes of multiple satellites at different altitudes during the September 2017 moderate storm. It is found that the storm-induced orbital decay rates of Swarm-B, Swarm-A, and GRACE satellites increased by 100%-150% depending on their altitudes. Overall, the results suggest that our integration approach has better performance than the previous approach in deriving the orbital decay rate at solar minimum or at high altitude when the atmospheric density is relatively low. **19-22 Nov 2003, 6-10 Sep 2017**

Visualizing CMEs and Predicting Geomagnetic Storms from Solar Magnetic Fields

Yan **Li** , Janet G. Luhmann, J. Todd. Hoeksema, Xuepu Zhao, C. Nick Arge

Space Weather Geophysical Monograph 125 **2001**

https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/GM125p0177

Because solar photospheric magnetic fields are the main source of the magnetic field in the corona and interplanetary space, changes in the photospheric field may be expected to drive transients in both regions. However, because the solar field is both complex and influenced by the solar wind, it is difficult to determine whether specific photospheric field features underlie the important transients called Coronal Mass Ejections (CMEs). Models enable us to link the photospheric field to coronal field changes and visualize the response. The potential field source surface (PFSS) model is known for its combination of relative simplicity and ability to approximate coronal hole geometry and eclipse images. We utilize PFSS models and specialized synoptic maps of the solar magnetic field to study the relationship between coronal field changes and CMEs, and to attempt to visualize CMEs and predict geomagnetic storms. For prediction purposes, updated synoptic maps in real time are needed. Several solar observatories and SOHO/MDI are currently providing such maps on a roughly daily basis, although the potential exists for hourly updates. Our results to date suggest that the combination of photospheric field observations and coronal models can provide a useful addition to the collection of space weather forecast tools.

Qualitative and Quantitative Assessment of the SET HASDM Database

Richard J. **Licata**, Piyush M. Mehta, W. Kent Tobiska, Bruce R. Bowman, Marcin D. Pilinski

Space Weather e2021SW002798 **Volume19, Issue8** **2021**

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021SW002798

https://doi.org/10.1029/2021SW002798

The High Accuracy **Satellite Drag Model** (HASDM) is the operational thermospheric density model used by the US Space Force (USSF) Combined Space Operations Center (CSpOC). By using real-time data assimilation, HASDM can provide density estimates with increased accuracy over other empirical models. With historical HASDM density data being released publicly for the first time, we can analyze the data to compare dominant modes of variability in the upper atmosphere as modeled by HASDM and the Jacchia-Bowman 2008 Empirical Thermospheric Density Model (JB2008), a Jacchia family model upon which density corrections are made as part of the HASDM framework. This model comparison is conducted through the use of Principal Component Analysis (PCA) which shows the increased variability of the HASDM dataset. We highlight HASDM's ability to capture the movement of lighter species during solar minimum conditions, unlike many empirical models. We then compare density from both models to the CHAllenging Minisatellite Payload (CHAMP) and Gravity Recovery and Climate Experiment (GRACE) accelerometer-derived density estimates. This comparison shows that HASDM more closely matches the accelerometer-derived densities with mean absolute differences of 23.84% and 30.93% compared to CHAMP and GRACE-A, respectively. The comparison also reveals improved representation of cooling mechanisms due to NO and CO2 by the HASDM database.

Benchmarking Forecasting Models for SpaceWeather Drivers

Richard J. **Licata** , W. Kent Tobiska , Piyush M. Mehta
Space Weather e2020SW002496 **2020**
https://doi.org/10.1029/2020SW002496
Space weather indices are commonly used to drive operational forecasts of various geospace systems, including the thermosphere for mass density and satellite drag. The drivers serve as proxies for various processes that cause energy flow and deposition in the geospace system. Forecasts of neutral mass density are a major uncertainty in operational orbit prediction and collision avoidance for objects in low earth orbit (LEO). For the strongly driven system, accuracy of space weather driver forecasts is crucial for operations. The High Accuracy Satellite Drag Model (HASDM) currently employed by the United States Air Force in an operational environment is driven by four (4) solar and two (2) geomagnetic proxies. Space Environment Technologies (SET) is contracted by the space command to provide forecasts for the drivers. This work performs a comprehensive assessment for the performance of the driver forecast models. The goal is to provide a benchmark for future improvements of the forecast models. Using an archived data set spanning six (6) years and 15,000 forecasts across solar cycle 24, we quantify the temporal statistics of the model performance.

Model Evaluation Guidelines for Geomagnetic Index Predictions

Michael W. **Liemohn** , James P. McCollough , Vania K. Jordanova , Chigomezyo M. Ngwira, Steven K. Morley, Consuelo Cid, W. Kent Tobiska, Peter Wintoft …
Space Weather 16?, 12, 2079-2102 **2018**
http://sci-hub.tw/10.1029/2018SW002067
Geomagnetic indices are convenient quantities that distill the complicated physics of some region or aspect of near-Earth space into a single parameter. Most of the best-known indices are calculated from ground-based magnetometer data sets, such as Dst, SYM-H, Kp, AE, AL, and PC. Many models have been created that predict the values of these indices, often using solar wind measurements upstream from Earth as the input variables to the calculation. This document reviews the current state of models that predict geomagnetic indices and the methods used to assess their ability to reproduce the target index time series. These existing methods are synthesized into a baseline collection of metrics for benchmarking a new or updated geomagnetic index prediction model. These methods fall into two categories: (1) fit performance metrics such as root-mean-square error and mean absolute error that are applied to a time series comparison of model output and observations and (2) event detection performance metrics such as Heidke Skill Score and probability of detection that are derived from a contingency table that compares model and observation values exceeding (or not) a threshold value. A few examples of codes being used with this set of metrics are presented, and other aspects of metrics assessment best practices, limitations, and uncertainties are discussed, including several caveats to consider when using geomagnetic indices.

Quo vadis, European Space Weather community? **Review**

Agora – Strategic or programmatic article

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https://www.swsc-journal.org/articles/swsc/pdf/2021/01/swsc200098.pdf
This paper was written by a group of European researchers believing that now is the right time to frame the Space Weather and Space Climate discipline in Europe for future years. It is devoted to openly discussing the organisation and sustainability of the European Space Weather community and its assets in the (near) future. More specifically, we suggest that the European Space Weather community lacks a uniting organisation to help the community to

sustain and develop the successful efforts made thus far. Our aim is not to draw a complete and exhaustive panorama of Space Weather throughout the world, nor even throughout Europe. It is not a new white paper on the science and applications: there exist many (e.g. Tsurutani et al., 2020 Nonlinear Processes Geophys 27(1): 75–119); nor another roadmap: several important have been published recently (e.g. Schrijver et al., 2015. Adv Space Res 55(12): 2745–2807; Opgenoorth et al., 2019. J Space Weather Space Clim 9: A37). Our aim is to question our practices and organisation in front of several changes that have occurred in the recent years and to set the ground to provide coordinated answers to these questions being posed in Europe, and to make these answers discussed throughout the world.

This group was assembled first through a series of sessions devoted to the sustainability of Space Weather research during the European Space Weather Week (ESWW) series of meetings, specifically: ESWW 14 (2017), ESWW 15 (2018), and ESWW 16 (2019). It then grew from discussions and personal contacts. The authors do not pretend to identify the full range of opinions in Europe, although they do come from 13 different European countries with a large span of ages (around half are below the age of 40 years old at the time of writing) with a good gender balance ending with a diverse mix of young and motivated scientists and senior people who have played a role in shaping the Space Weather community in Europe. The questions and the propositions to organise Space Weather in Europe in the future result from their discussions through these meetings and through remote meetings during the pandemic. We wish to share them with all those who consider themselves as members of the European Space Weather community and/or are interested in its future and to propose actions. We do this, bearing in mind that Europe plays a key international role in Space Weather which extends beyond the ESA and EU/EC geographic area.

What characterizes planetary space weather? **Review**

Jean **Lilensten**, Andrew J. Coates, Véronique Dehant, Thierry Dudok de Wit, Richard B. Horne, François Leblanc, Janet Luhmann, Emma Woodfield, Mathieu Barthélemy

The Astronomy and Astrophysics Review, November **2014**, 22:79,
http://download.springer.com/static/pdf/105/art%253A10.1007%252Fs00159-014-0079-6.pdf?auth66=1417242552_fd6e55aac9dbbc4fb0a04b5cdb422f9d&ext=.pdf

Space weather has become a mature discipline for the Earth space environment. With increasing efforts in space exploration, it is becoming more and more necessary to understand the space environments of bodies other than Earth. This is the background for an emerging aspect of the space weather discipline: planetary space weather. In this article, we explore what characterizes planetary space weather, using some examples throughout the solar system. We consider energy sources and timescales, the characteristics of solar system objects and interaction processes. We discuss several developments of space weather interactions including the effects on planetary radiation belts, atmospheric escape, habitability and effects on space systems. We discuss future considerations and conclude that planetary space weather will be of increasing importance for future planetary missions.

Thermospheric Neutral Density Variation during the “SpaceX” Storm: Implications from Physics-based Whole Geospace Modeling

Dong **Lin**, Wenbin Wang, Katherine Garcia-Sage, Jia Yue, Viacheslav Merkin, Joseph M. McInerney, Kevin Pham, Kareem Sorathia

Space Weather e2022SW003254 Volume20, Issue12 **2022**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022SW003254
https://doi.org/10.1029/2022SW003254

The Starlink satellites launched on **3 February 2022** were lost before they fully arrived in their designated orbits. The loss was attributed to two moderate geomagnetic storms that occurred consecutively on **February 3-4**. We investigate the thermospheric neutral mass density variation during these storms with the Multiscale Atmosphere-Geospace Environment (MAGE) model, a first-principles, fully coupled geospace model. Simulated neutral density enhancements are validated by Swarm satellite measurements at the altitude of 400-500 km. Comparison with standalone TIEGCM and empirical NRLMSIS 2.0 and DTM-2012 models suggests better performance by MAGE in predicting the maximum density enhancement and resolving the gradual recovery process. Along the Starlink satellite orbit in the middle thermosphere (~200 km altitude), MAGE predicts up to 150% density enhancement near the second storm peak while standalone TIEGCM, NRLMSIS 2.0 and DTM-2012 suggest only ~50% increase. MAGE also suggests altitudinal, longitudinal, and latitudinal variability of storm-time percentage density enhancement due to height dependent Joule heating deposition per unit mass, thermospheric circulation changes, and travelling atmospheric disturbances. This study demonstrates that a moderate storm can cause substantial density enhancement in the middle thermosphere. Thermospheric mass density strongly depends on the strength, timing, and location of high-latitude energy input, which cannot be fully reproduced with empirical models. A physics-based, fully coupled geospace model that can accurately resolve the high-latitude energy input and its variability is critical to modeling the dynamic response of thermospheric neutral density during storm time.

Seismic imaging of the Sun's far hemisphere and its applications in space weather forecasting

Charles **Lindsey**, Douglas Braun

Space Weather Volume 15, Issue 6 June **2017** Pages 761–781

http://onlinelibrary.wiley.com/doi/10.1002/2016SW001547/full

http://sci-hub.cc/10.1002/2016SW001547

The interior of the Sun is filled acoustic waves with periods of about 5 min. These waves, called “p modes,” are understood to be excited by convection in a thin layer beneath the Sun's surface. The p modes cause seismic ripples, which we call “the solar oscillations.” Helioseismic observatories use Doppler observations to map these oscillations, both spatially and temporally. The p modes propagate freely throughout the solar interior, reverberating between the near and far hemispheres. They also interact strongly with active regions at the surfaces of both hemispheres, carrying the signatures of said interactions with them. Computational analysis of the solar oscillations mapped in the Sun's near hemisphere, applying basic principles of wave optics to model the implied p modes propagating through the solar interior, gives us seismic maps of large active regions in the Sun's far hemisphere. These seismic maps are useful for space weather forecasting. For the past decade, NASA's twin STEREO spacecraft have given us full coverage of the Sun's far hemisphere in electromagnetic (EUV) radiation from the far side of Earth's orbit about the Sun. We are now approaching a decade during which the STEREO spacecraft will lose their farside vantage. There will occur significant periods from thence during which electromagnetic coverage of the Sun's far hemisphere will be incomplete or nil. Solar seismology will make it possible to continue our monitor of large active regions in the Sun's far hemisphere for the needs of space weather forecasters during these otherwise blind periods.

Forbush Decreases during the DeepMin and MiniMax of Solar Cycle 24

Lingri, D.; Mavromichalaki, H.; Belov, A.; Eroshenko, E.; Yanke, V.; Abunin, A.; Abunina, M.

XXV ECRS **2016** Proceedings

https://arxiv.org/pdf/1612.08900.pdf

Solar Physics, Volume 291, Issue 3, pp.1025-1041, 2016

After a prolong and deep solar minimum at the end of solar cycle 23, the current cycle 24 is one of the lowest cycles. The two periods of deep minimum and mini-maximum of the cycle 24 are connected by a period of increasing solar activity. In this work, the Forbush decreases of cosmic ray intensity during the period from January 2008 to December 2014 are studied. A statistical analysis of 749 events using the IZMIRAN database of Forbush effects obtained by processing the data of the worldwide neutron monitor network using the global survey method is performed. A further study of the events that happened on the Sun and affected the interplanetary space, and finally provoked the decreases of the galactic cosmic rays near Earth is performed. A statistical analysis of the amplitude of the cosmic ray decreases with solar and geomagnetic parameters is carried out. The results will be useful for space weather studies and especially for Forbush decreases forecasting. **17 March 2013**

TABLE I: List of FDs with amplitude greater than 5% (2011-2014)

Coupled MHD-Focused Transport Simulations for Modeling Solar Particle Events

Jon A. **Linker**, Ronald M. Caplan, Nathan Schwadron, Matthew Gorby, Cooper Downs, Tibor Torok, Roberto Lionello, Janvier Wijaya

Journal of Physics Conf. Ser. ASTRONUM 2018 **2019**

https://arxiv.org/pdf/1905.05299.pdf

We describe the initial version of the Solar Particle Event (SPE) Threat Assessment Tool or STAT. STAT relies on elements of Corona-Heliosphere (CORHEL) and the Earth-Moon-Mars Radiation Environment Module (EMMREM), and allows users to investigate coronal mass ejection (CME) driven SPEs using coupled magnetohydrodynamic (MHD) and focused transport solutions. At the present time STAT focuses on modeling solar energetic particle (SEP) acceleration in and transport from the low corona, where the highest energy SEP events are generated. We illustrate STAT's capabilities with a model of the **July 14, 2000** "Bastille Day" event, including innovative diagnostics for understanding the three-dimensional distribution of particle fluxes and their relation to the structure of the underlying CME driver. A preliminary comparison with NOAA GOES measurements is shown.

Global Observations of Geomagnetically Induced Currents Caused by an Extremely Intense Density Pulse During a Coronal Mass Ejection

Terry Z. **Liu**, Xueling Shi, Michael D. Hartinger, Vassilis Angelopoulos, Craig J. Rodger, Ari Viljanen, Yi Qi, Chen Shi, Hannah Parry, Ian Mann, Darcy Cordell … See all authors

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https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2024SW003993

A variety of magnetosphere-ionosphere current systems and waves have been linked to geomagnetic disturbance (GMD) and geomagnetically induced currents (GIC). However, since many location-specific factors control GMD and GIC intensity, it is often unclear what mechanisms generate the largest GMD and GIC in different locations. We address this challenge through analysis of multi-satellite measurements and globally distributed magnetometer and GIC measurements. We find embedded within the magnetic cloud of the **23–24 April 2023** coronal mass ejection (CME) storm there was a global scale density pulse lasting for 10–20 min with compression ratio of ∼10. It caused substantial dayside displacements of the bow shock and magnetopause, changes of 6 RE and 1.3−2 RE, respectively, which in turn caused large amplitude GMD in the magnetosphere and on the ground across a wide local time range. At the time this global GMD was observed, GIC measured in New Zealand, Finland, Canada, and the United States were observed. The GIC were comparable (within factors of 2–2.5) to the largest ever recorded during ≥14 year monitoring intervals in New Zealand and Finland and represented ∼2-year maxima in the United States during a period with several Kp≥7 geomagnetic storms. Additionally, the GIC measurements in the USA and other mid-latitude locations exhibited wave-like fluctuations with 1–2 min period. This work suggests that large density pulses in CME should be considered an important driver of large amplitude, global GMD and among the largest GIC at mid-latitude locations, and that sampling intervals ≤10 s are required to capture these GMD/GIC.

The Radiation Impact of Solar Energetic Particle Events on the Moon: A Statistical Study Using Data-Based Modeling Results

Bailiang **Liu**, Jingnan Guo, Yubao Wang, Mikhail I. Dobynde
Space Weather Volume22, Issue11 November **2024** e2024SW004086
https://doi.org/10.1029/2024SW004086
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2024SW004086
The Moon lacks a global magnetic field and atmosphere, leaving its surface been directly exposed to high-energy cosmic radiation. Sporadic Solar Particle Events are sources of a significant radiation exposure, potentially posing serious threats to the health of astronauts exploring the Moon. In this paper, we use the Radiation Environment and Dose at the Moon (REDMoon) model based on GEometry And Tracking (GEANT4) Monte-Carlo method to calculate the body effective dose induced by 262 large historical SEP events on the Moon under different shielding depths which can result from the lunar regolith shielding and/or additional aluminum shielding. We calculate and compare the contributions of different particles from or produced by SEPs to the total body effective dose. Additionally, we develop empirical functions to rapidly assess SEP-induced effective dose on the Moon under different shielding scenarios.

Predicting Solar Flares Using a Long Short-Term Memory Network

Hao **Liu**, Chang Liu, Jason T. L. Wang, Haimin Wang
2019
https://arxiv.org/pdf/1905.07095.pdf
We present a long short-term memory (LSTM) network for predicting whether an active region (AR) would produce a gamma-class flare within the next 24 hours. We consider three gamma classes, namely >=M5.0 class, >=M class, and >=C class, and build three LSTM models separately, each corresponding to a gamma class. Each LSTM model is used to make predictions of its corresponding gamma-class flares. The essence of our approach is to model data samples in an AR as time series and use LSTMs to capture temporal information of the data samples. Each data sample has 40 features including 25 magnetic parameters obtained from the Space-weather HMI Active Region Patches (SHARP) and related data products as well as 15 flare history parameters. We survey the flare events that occurred from 2010 May to 2018 May, using the GOES X-ray flare catalogs provided by the National Centers for Environmental Information (NCEI), and select flares with identified ARs in the NCEI flare catalogs. These flare events are used to build the labels (positive vs. negative) of the data samples. Experimental results show that (i) using only 14-22 most important features including both flare history and magnetic parameters can achieve better performance than using all the 40 features together; (ii) our LSTM network outperforms related machine learning methods in predicting the labels of the data samples. To our knowledge, this is the first time that LSTMs have been used for solar flare prediction.

Quantitative influence of coast effect on geomagnetically induced currents in power grids: a case study

Chunming **Liu**, Xuan Wang, Hongmei Wang and Huilun Zhao
J. Space Weather Space Clim. **2018**, 8, A60
https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc180028.pdf
In recent years, several magnetic storms have disrupted the normal operation of power grids in the mid-low latitudes. Data obtained from the monitoring of geomagnetically induced currents (GIC) indicate that GIC tend to be elevated at nodes near the ocean-land interface. This paper discusses the influence of the geomagnetic coast effect on GIC in power grids based on geomagnetic data from a coastal power station on November 9, 2004. We used a three-dimensional (3D) Earth conductivity model to calculate the induced electric field using the finite element

method (FEM), and compared it to a one-dimensional (1D) layered model, which could not incorporate a coastal effect. In this manner, the GIC in the Ling'ao power plant was predicted while taking the coast effect into consideration in one case and ignoring it in the other. We found that the GIC predicted by the 3D model, which took the coastal effect into consideration, showed only a 2.9% discrepancy with the recorded value, while the 1D model underestimated the GIC by 23%. Our results demonstrate that the abrupt lateral variations of Earth conductivity structures significantly influence GIC in the power grid. We can infer that high GIC may appear even at mid-low latitude areas that are subjected to the coast effect. Therefore, this effect should be taken into consideration while assessing GIC risk when power networks are located in areas with lateral shifts in Earth conductivity structures, such as the shoreline and the interfaces of different geological structures.

Analysis of the monitoring data of geomagnetic storm interference in the electrification system of a high-speed railway

Lianguang **Liu**, Xiaoning Ge, Wei Zong, You Zhou,
Space Weather Volume 14, Issue 10 October **2016** Pages 754–763
http://sci-hub.cc/doi/10.1002/2016SW001411
To study the impact of geomagnetic storm on the equipment of traction electrification system in the high-speed railway, geomagnetically induced current (GIC) monitoring devices were installed in the Hebi East traction power supply substation of the Beijing-Hong Kong Dedicated Passenger Line in January 2015, and GICs were captured during the two geomagnetic storms on **17 March and 23 June 2015**. In order to investigate the GIC flow path, both in the track circuit and in the traction network adopting the autotransformer feeding system, a GIC monitor plan was proposed for the electrical system in the Hebi East traction power supply substation. This paper analyzes the correlation between the GIC captured on 17 March and the geomagnetic data obtained from the Malingshan Geomagnetic Observatory and presents a regression analysis between the measured GIC and the calculated geoelectric fields on 23 June in the high-speed railway. The maximum GICs measured in the track circuit are 1.08 A and 1.74 A during the two geomagnetic storms. We find that it is necessary to pay attention on the throttle transformers and track circuits, as the most sensitive elements responding to the extreme geomagnetic storms in the high-speed railway.

Operational Space Weather Services in National Space Science Center of Chinese Academy of Sciences

Siqing **Liu** and Jiancun Gong
Space Weather Volume 13, Issue 10 (pages 599–605) **2015**
Space Weather Quarterly Vol. 12, Issue 4, **2015**
http://onlinelibrary.wiley.com/doi/10.1002/2015SW001298/full
http://onlinelibrary.wiley.com/doi/10.1002/2015SW001298/epdf
http://onlinelibrary.wiley.com/doi/10.1002/SWQv12i004/epdf

Cosmic Meteorology

Mike **Lockwood**, Mat Owens
Astronomy and Geophysics **2021**
https://arxiv.org/ftp/arxiv/papers/2105/2105.12559.pdf
Mike Lockwood and Mathew Owens discuss how eclipse observations are aiding the development of a climatology of near-Earth space. **2009 July 22, 2013 November 3, 2019 July 2, 14 December 2020**

The Development of a Space Climatology: 3. Models of the Evolution of Distributions of Space Weather Variables With Timescale

Mike **Lockwood** Sarah N. Bentley Mathew J. Owens Luke A. Barnard Chris J. Scott Clare E. Watt Oliver Allanson Mervyn P. Freeman
Space Weather 17(1) 180-209 **2019**
http://sci-hub.tw/10.1029/2018SW002017
We study how the probability distribution functions of power input to the magnetosphere $P\alpha$ and of the geomagnetic ap and Dst indices vary with averaging timescale, τ, between 3 hr and 1 year. From this we develop and present algorithms to empirically model the distributions for a given τ and a given annual mean value. We show that lognormal distributions work well for ap, but because of the spread of Dst for low activity conditions, the optimum formulation for Dst leads to distributions better described by something like the Weibull formulation. Annual means can be estimated using telescope observations of sunspots and modeling, and so this allows the distributions to be estimated at any given τ between 3 hr and 1 year for any of the past 400 years, which is another important step toward a useful space weather climatology. The algorithms apply to the core of the distributions and

can be used to predict the occurrence rate of large events (in the top 5% of activity levels): they may contain some, albeit limited, information relevant to characterizing the much rarer superstorm events with extreme value statistics. The algorithm for the Dst index is the more complex one because, unlike ap, Dst can take on either sign and future improvements to it are suggested.

The Development of a Space Climatology: 2. The Distribution of Power Input Into the Magnetosphere on a 3-Hourly Timescale

Mike **Lockwood** Sarah N. Bentley Mathew J. Owens Luke A. Barnard Chris J. Scott Clare E. Watt Oliver Allanson Mervyn P. Freeman

Space Weather 17(1) 157-179 **2019**

http://sci-hub.tw/10.1029/2018SW002016

Paper 1 in this series (Lockwood et al., 2018a, https://doi.org/10.1029/2018SW001856) showed that the power input into the magnetosphere Pα is an ideal coupling function for predicting geomagnetic “range” indices that are strongly dependent on the substorm current wedge and that the optimum coupling exponent α is 0.44 for all averaging timescales, τ, between 1 min and 1 year. The present paper explores the implications of these results. It is shown that the form of the distribution of Pα at all averaging timescales τ is set by the interplanetary magnetic field orientation factor via the nature of solar wind-magnetosphere coupling (due to magnetic reconnection in the dayside magnetopause) and that at τ = 3 hr (the timescale of geomagnetic range indices) the normalized Pα (divided by its annual mean, that is, <Pα >τ=3hr/<Pα >τ=1yr) follows a Weibull distribution with k of 1.0625 and λ of 1.0240. This applies to all years to a useful degree of accuracy. It is shown that exploiting the constancy of this distribution and using annual means to predict the full distribution gives the probability of space weather events in the largest 10% and 5% to within uncertainties of magnitude 10% and 12%, respectively, at the one sigma level.

The Development of a Space Climatology: 1. Solar Wind Magnetosphere Coupling as a Function of Timescale and the Effect of Data Gaps

Mike **Lockwood** Sarah N. Bentley Mathew J. Owens Luke A. Barnard Chris J. Scott Clare E. Watt Oliver Allanson

Space Weather 17(1) 133-156 **2019**

sci-hub.tw/10.1029/2018SW001856

Different terrestrial space weather indicators (such as geomagnetic indices, transpolar voltage, and ring current particle content) depend on different coupling functions(combinations of near-Earth solar wind parameters), and previous studies also reported a dependence on the averaging timescale, τ. We study the relationships of the am and SME geomagnetic indices to the power input into the magnetosphere Pα, estimated using the optimum coupling exponent α, for a range of τ between 1 min and 1 year. The effect of missing data is investigated by introducing synthetic gaps into near-continuous data, and the best method for dealing with them when deriving the coupling function is formally defined. Using Pα, we show that gaps in data recorded before 1995 have introduced considerable errors into coupling functions. From the near-continuous solar wind data for 1996–2016, we find that α = 0.44 ± 0.02 and no significant evidence that αdepends on τ, yielding $P\alpha \propto B^{0.88} V_{sw}^{1.90} (m_{sw} N_{sw})^{0.23} \sin^4(\theta/2)$, where B is the interplanetary magnetic field, Nsw the solar wind number density, msw its mean ion mass, Vsw its velocity, and θ the interplanetary magnetic field clock angle in the geocentric solar magnetospheric reference frame. Values of Pα that are accurate to within ±5% for 1996–2016 have an availability of 83.8%, and the correlation between Pα and am for these data is shown to be 0.990 (between 0.972 and 0.997 at the 2σ uncertainty level), 0.897 ± 0.004, and 0.790 ± 0.03, for τ of 1 year, 1 day, and 3 hr, respectively, and that between Pα and SME at τ of 1 min is 0.7046 ± 0.0004.

Space climate and space weather over the past 400 years: 2. Proxy indicators of geomagnetic storm and substorm occurrence

Mike **Lockwood**, Mathew J. Owens, Luke A. Barnard, Chris J. Scott, Clare E. Watt and Sarah Bentley

J. Space Weather Space Clim. **2018**, 8, A12

https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc170036.pdf

Using the reconstruction of power input to the magnetosphere presented in Paper 1 Lockwood et al. [J Space Weather Space Clim 7 (2017a)], we reconstruct annual means of the geomagnetic Ap and AE indices over the past 400 years to within a 1-sigma error of ±20%. In addition, we study the behaviour of the lognormal distribution of daily and hourly values about these annual means and show that we can also reconstruct the fraction of geomagnetically-active (storm-like) days and (substorm-like) hours in each year to accuracies of to accuracies of ~50%, including the large percentage uncertainties in near-zero values. The results are the first physics-based quantification of the space weather conditions in both the Dalton and Maunder minima. Looking to the future, the weakening of Earth's magnetic moment means that the terrestrial disturbance levels during a future repeats of the solar Dalton and Maunder minima will be weaker and we here quantify this effect for the first time.

Space climate and space weather over the past 400 years: 1. The power input to the magnetosphere

Mike **Lockwood***, Mathew J. Owens, Luke A. Barnard, Chris J. Scott and Clare. E. Watt

J. Space Weather Space Clim. **2017**, 7, A25
https://www.swsc-journal.org/articles/swsc/pdf/2017/01/swsc170035.pdf
Using information on geomagnetic activity, sunspot numbers and cosmogenic isotopes, supported by historic eclipse images and in conjunction with models, it has been possible to reconstruct annual means of solar wind speed and number density and heliospheric magnetic field (HMF) intensity since 1611, when telescopic observations of sunspots began. These models are developed and tuned using data recorded by near-Earth interplanetary spacecraft and by solar magnetograms over the past 53 years. In this paper, we use these reconstructions to quantify power input into the magnetosphere over the past 400 years. For each year, both the annual mean power input is computed and its distribution in daily means. This is possible because the distribution of daily values divided by the annual mean is shown to maintain the same lognormal form with a constant variance. This study is another important step towards the development of a physics-based, long-term climatology of space weather conditions.

PRESTO – Predictability of the Variable Solar-Terrestrial Coupling

R.E. **Lopez**1, K. Matthes2,3 and J. Zhang4
SCOSTEP_PRESTO_Newsletter_Vol22.pdf **2020** **File**

The March 1940 Superstorm: Geoelectromagnetic Hazards and Impacts on American Communication and Power Systems

Jeffrey J. **Love**, E. Joshua Rigler, Michael D. Hartinger, Greg M. Lucas, Anna Kelbert, Paul A. Bedrosian
Space Weather Volume21, Issue6 June **2023** e2022SW003379
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022SW003379
An analysis is made of geophysical records of the **24 March 1940**, magnetic storm and related reports of interference on long-line communication and power systems across the contiguous United States and, to a lesser extent, Canada. Most long-line system interference occurred during local daytime, after the second of two storm sudden commencements and during the early part of the storm's main phase. The high degree of system interference experienced during this storm is inferred to have been due to unusually large-amplitude and unusually rapid geomagnetic field variation, possibly driven by interacting interplanetary coronal-mass ejections. Geomagnetic field variation, in turn, induced geoelectric fields in the electrically conducting solid Earth, establishing large potential differences (voltages) between grounding points at communication depots and transformer substations connected by long transmission lines. It is shown that March 1940 storm-time communication- and power-system interference was primarily experienced over regions of high electromagnetic surface impedance, mainly in the upper Midwest and eastern United States. Potential differences measured on several grounded long lines during the storm exceeded 1-min resolution voltages that would have been induced by the March 1989 storm. In some places, voltages exceeded American electric-power-industry benchmarks. It is concluded that the March 1940 magnetic storm was unusually effective at inducing geoelectric fields. Although modern communication systems are now much less dependent on long electrically conducting transmission lines, modern electric-power-transmission systems are more dependent on such lines, and they, thus, might experience interference with the future occurrence of a storm as effective as that of March 1940.

Some experiments in extreme-value statistical modeling of magnetic superstorm intensities

Jeffrey J. **Love**
Space Weather **2020**
sci-hub.se/10.1029/2019SW002255
In support of projects for forecasting and mitigating the deleterious effects of extreme space-weather storms, an examination is made of the intensities of magnetic superstorms recorded in the Dst index time series (1957-2016). Modified peak-over-threshold and solar-cycle, block-maximum sampling of the Dst time series are performed to obtain compilations of storm-maximum -Dstm intensity values. Lognormal, upper-limit lognormal, generalized Pareto, and generalized extreme-value model distributions are fitted to the -Dstm data using a maximum-likelihood algorithm. All four candidate models provide good representations of the data. Comparisons of the statistical significance and goodness of fits of the various models gives no clear indication as to which model is best. The statistical models are used to extrapolate to extreme-value intensities, such as would be expected (on average) to occur once per century. An upper-limit lognormal fit to peak-over-threshold -Dstm data above a superstorm threshold of 283 nT gives a 100-year extrapolated intensity of 542 nT and a 68% confidence interval (obtained by bootstrap resampling) of [466, 583] nT. An upper-limit lognormal fit to solar-cycle, block-maximum data gives a 9-solar-cycle (approximately 100-year) extrapolated intensity of 553 nT. The Dst data are found to be insufficient for providing usefully accurate estimates of a statistically theoretical upper limit for magnetic storm intensity. Secular change in storm intensities is noted, as is a need for improved estimates of pre-1957 magnetic storm intensities.

Intensity and impact of the New York Railroad superstorm of May 1921

Jeffrey J. **Love**, Hisashi Hayakawa, Edward W. Cliver

Space Weather Volume17, Issue8 Pages 1281-1292 **2019**

sci-hub.se/10.1029/2019SW002250

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019SW002250

Analysis is made of low-latitude ground-based magnetometer data recording the magnetic superstorm of **May 1921**. By inference, the storm was driven by a series of interplanetary coronal mass ejections, one of which produced a maximum pressure on the magnetopause of ~64.5 nPa, sufficient to compress the subsolar magnetopause radius to ~5.3 Earth radii. Over the course of the storm, low-latitude geomagnetic disturbance exhibited extreme local-time (longitude) asymmetry that can be attributed to substorm disturbance extending to low latitudes. The storm attained an estimated maximum **-**Dst on **May 15** of 907 nT ±132 nT, an intensity comparable to that of the Carrington event of 1859. The May 1921 storm interfered with and damaged telephone and telegraph systems associated with railroad systems in New York City and State. These effects were due to a combination of three factors: the localized details of geomagnetic vector disturbance, the geographic expression of the Earth's surface impedance tensor, and the configurations and physical parameters of the electrical networks of the day.

Chapter 9 - Extreme-Event Geoelectric Hazard Maps **Review**

Jeffrey J.**Love**, Paul A.Bedrosian†

In: Extreme Events in Geospace Origins, Predictability, and Consequences **2018**, Pages 209-230

http://sci-hub.tw/10.1016/B978-0-12-812700-1.00009-1

Maps of geoelectric amplitude covering about half the continental United States are presented that will be exceeded, on average, once per century in response to an extreme-intensity geomagnetic disturbance. These maps are constructed using an empirical parameterization of induction: convolving latitude-dependent statistical maps of extreme-value geomagnetic disturbances, obtained from decades of 1-minute magnetic observatory data, with local estimates of Earth-surface impedance obtained at discrete geographic sites from magnetotelluric surveys. Geoelectric amplitudes are estimated for geomagnetic waveforms having a 240-s (and 1200-s) sinusoidal period and amplitudes over 10 min (1 h) that exceed a once-per-century threshold. As a result of the combination of geographic differences in geomagnetic variation and Earth-surface impedance, once-per-century geoelectric amplitudes span more than two orders of magnitude and are a highly granular function of location. Specifically for north-south 240-s induction, once-per-century geoelectric amplitudes across large parts of the United States have a median value of 0.34 V/km; for east-west variation, they have a median value of 0.23 V/km. In Northern Minnesota, amplitudes exceed 14.00 V/km for north-south geomagnetic variation (23.34 V/km for east-west variation), while just over 100 km away, amplitudes are only 0.08 V/km (0.02 V/km). At some sites in the northern-central United States, once-per-century geoelectric amplitudes exceed the 2 V/km realized in Québec during the March 1989 storm.

The Electric Storm of November 1882

Jeffrey J. **Love**

Space Weather 12 January **2018** Vol: 16, Pages: 37–46

http://sci-hub.tw/10.1002/2017SW001795

In November 1882, an intense magnetic storm related to a large sunspot group caused widespread interference to telegraph and telephone systems and provided spectacular and unusual auroral displays. The (ring current) storm time disturbance index for this storm reached maximum −Dst ≈ 386 nT, comparable to Halloween storm of 29–31 October 2003, but from 17 to 20 November the aa midlatitude geomagnetic disturbance index averaged 214.25 nT, the highest 4 day level of disturbance since the beginning of aa index in 1868. This storm contributed to scientists' understanding of the reality of solar-terrestrial interaction. Past occurrences of magnetic storms, like that of November 1882, can inform modern evaluations of the deleterious effects that a magnetic superstorm might have on technological systems of importance to society.

The USGS Geomagnetism Program and Its Role in Space Weather Monitoring

Love, Jeffrey J.; Finn, Carol A.

Space Weather, Vol. 9, No. 7, S07001, **2011**

http://dx.doi.org/10.1029/2011SW000684

The U.S. Geological Survey Geomagnetism Program, which operates a network of ground-based magnetic observatories, plays an important role in space weather monitoring.

Magnetic storms result from the dynamic interaction of the solar wind with the coupled magnetospheric-ionospheric system. Large storms represent a potential hazard for the activities and infrastructure of a modern, technologically based society [Baker et al., 2008]; they can cause the loss of radio communications, reduce the accuracy of global positioning systems, damage satellite electronics and affect satellite operations, increase pipeline corrosion, and induce voltage surges in electric power grids, causing blackouts. So while space weather starts with the Sun and is driven by the solar wind, it is on, or just above, the surface of the Earth that the practical effects of space weather are realized. Therefore, ground-based sensor networks, including magnetic observatories [Love, 2008], play an important role in space weather monitoring.

Solar Particle Event Dose Forecasting Using Regression Techniques

Alan Mitchel **Lovelace**, Al Maqsudur Rashid, Wouter C. de Wet, Lawrence W. Townsend, J. Wesley Hines, Hanna Moussa

Space Weather Volume16, Issue8 August **2018** Pages 1073-1085

http://sci-hub.tw/10.1029/2017SW001773

Doses from solar particle events can be a serious threat to the wellbeing of crews traveling through space. Therefore, methods for predicting the time such events will take place, methods for forecasting the dose buildup over time, and methods for forecasting the potential total dose from such events are needed to enable crews to take actions to mitigate the effects by entering a shielded area designed for their protection. This work focuses on forecasting the total dose expected for an event, based upon doses obtained very early in the event, using the kernel regression method. The model uses tables of calculated doses for historical solar particle events augmented with hypothetical events similar to the actual ones for training purposes. Reasonably accurate predictions of the total dose expected for an event can be made within the first hour after event onset. Predictive accuracies generally increase as the event progresses in time. The only inputs required are doses and times since event onset as provided by dosimetry devices. One hundred thirteen actual events with total doses between 1 and 1,000 cGy were tested using the model. At 1 hr into the event, total dose predictions were within ±30% of the actual total doses for 91 events (81%) and within ±15% for 54 of them (48%). Within the first 4 hr following event onset, total dose predictions were within ±30% for 98 events (87%) and within ±15% for 66 of them (58%). A software package implementing the model has been provided to the Space Radiation Analysis Group at NASA Johnson Space for incorporation into their operational procedures for analyzing possible threats to space crews from solar particle events.

Space Weather into the 2030s: The 2024 Solar and Space Physics Decadal Survey

Noé **Lugaz**

Space Weather Quarterly: December **2024**

https://d197for5662m48.cloudfront.net/documents/publicationstatus/235412/preprint_pdf/0b0cd527ab9569cd09d2bcd2ed0e8caa.pdf

The report of the 2024 decadal survey for the solar and space physics community was released on 2024 December 5 and has space weather science and applications as a central goal to explore and safeguard humanity's home in space. I discuss some of the main recommendations associated with space weather that will drive our field in the next decade.

2024 Decadal Survey for Space and Solar Physics: Space Weather Inputs

FROM THE EDITORS

Noé **Lugaz**, Jennifer Gannon, Shasha Zou, Steven Morley, Huixin Liu, Brett Carter

Space Weather **Volume20, Issue8** e2022SW003181 **2022**

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022SW003181

Space Weather Quarterly: June **2022**

https://www.essoar.org/pdfjs/10.1002/essoar.10511555.1

The next decadal survey process for space and solar physics will start soon with white papers due during the second half of 2022 and the committees and panels working over all of 2023. Space weather science and operations will play an essential role in this survey. Therefore, the community is invited to prepare white papers and get involved in advancing space weather research and capabilities in the upcoming decades. A summary of the recommendations related to space weather from the last two decadal surveys is also provided.

Space Weather as the Nexus of Applied and Fundamental Space Science: The Need for Separate Funding Mechanisms and Definition

Noé **Lugaz** , Jennifer Gannon , Michael Hapgood , Huixin Liu , T Paul O'Brien

Space Weather **Volume19, Issue2** e2020SW002695 **2021**

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020SW002695

https://doi.org/10.1029/2020SW002695

This editorial aims at highlighting the importance of keeping space science and space weather fundamental and applied research highly interconnected, but also separate through distinct funding mechanisms. Fundamental and applied space research endeavors are not the same, even though they may share some of the same science regions and approaches, and scientists.

PROSWIFT Bill and the 2020 Space Weather Operations and Research Infrastructure Workshop From the National Academies of Sciences, Engineering, and Medicine
Noé **Lugaz**
Space Weather Volume18, Issue10 October **2020** e2020SW002628
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020SW002628
The Space Weather Research and Forecasting Act (PROSWIFT) passed the U.S. Senate in July 2020 and the House of Representative on 16 September; it directs NOAA to capture remote images of coronal mass ejections (CMEs) with the Space Weather Follow-On at L1 (SWFO-L1) mission. A workshop organized by an ad hoc committee of the National Academies of Sciences, Engineering, and Medicine had its second part held in 9–11 September 2020 to discuss future space weather operations and research infrastructure in the medium term. Discussions included low-Earth orbit (LEO) constellations, measurements of geomagnetically induced currents (GICs) and future cislunar and interplanetary measurements.

Chapter 10 - Space Weather at Earth and in Our Solar System **Review**
Noé **Lugaz**
In: ***The Sun as a Guide to Stellar Physics*** ***Book***
Eds. Oddbjørn Engvold, Jean-Claude Vial, and Andrew Skumanich
Elsevier , November **2018**
https://www.sciencedirect.com/book/9780128143346/the-sun-as-a-guide-to-stellar-physics
The solar wind, flares, solar eruptions, and energetic particles are able to affect the near-Earth geospace directly through a variety of physical mechanisms. This is referred to as “space weather,” which is discussed in this chapter. At Earth, this occurs primarily through solar radio emissions, heating of the upper atmosphere by the additional ultraviolet radiation associated with flares, and compression and reconnection of Earth's magnetic field by the solar wind and interplanetary transients. These interactions between Earth's environment and these solar and interplanetary phenomena also occur in slightly different forms at other planets in our solar system and are thought to exist in many other exoplanetary systems. Here, we review past decades of space weather research in the solar system and discuss parallels to exoplanetary systems.

Eruptive Prominences and Their Impact on the Earth and Our Life **Review**
Noé **Lugaz**
Solar Prominences
Astrophysics and Space Science Library Volume 415, **2015**, pp 433-453
http://link.springer.com/chapter/10.1007/978-3-319-10416-4_17
Following prominence eruptions (see Chap. 16: Webb, Solar prominences. New York: Springer, 2014), the associated coronal mass ejections (CMEs) propagate into the solar wind and interplanetary medium. While the complex interactions with the magnetic field and plasma in the corona (see Chaps. 15 and 16: Gopalswamy, Solar prominences. New York: Springer, 2014; Webb, Solar prominences. New York: Springer, 2014) have been observed for decades, it has only been in the last decade that the interaction of CMEs with the interplanetary medium can be directly imaged. As CMEs and prominences impact Earth, Earth’s magnetosphere may be disrupted through reconnection and/or compression, resulting in geomagnetic storms. In the most extreme cases, CMEs and prominences may have a global effect on man-made technologies and human beings, especially if they are in space. The conditions in the near-Earth environment directly affected by the Sun and the solar activity are known as space weather and will be discussed here.
In this chapter, we review different types of measurements and observations of prominences and CMEs as they propagate between the Sun and the Earth, as well as recent advances in numerical modeling and theoretical ideas related to CME propagation. We also discuss the potential effects of CMEs and prominences on Earth’s magnetosphere and atmosphere and the very direct impact it may exert on our lives.

Studying the Fixing Rate of GPS PPP Ambiguity Resolution Under Different Geomagnetic Storm Intensities
Xiaomin **Luo**, Zhuang Chen, Shengfeng Gu, Neng Yue, Tao Yue
Space Weather Volume21, Issue10 e2023SW003542 **2023**
https://doi.org/10.1029/2023SW003542
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2023SW003542
Global Positioning System (GPS) Precise Point Positioning (PPP) with correct fixing ambiguity resolution (AR) can reach cm-mm level positioning accuracy. However, this accuracy can be degraded by the geomagnetic storm effects. To comprehensively investigate the ambiguity resolved percentage (ARP) of GPS kinematic PPP, referred to as PPP-ARP, under different intensities of geomagnetic storms, based on the Natural Resources Canada's Canadian Spatial Reference System (CSRS) PPP, this study for the first time gives the correlation between the PPP-ARP and storm intensity using 67 storms occurred in the past 5 years of 2018–2022. Experimental results indicate that the

PPP-ARP decreases gradually as the increase of geomagnetic storm intensity. Under quiet and low geomagnetic conditions (Dstmin > −50 nT), the PPP-ARP of global GNSS stations can achieve more than 96%, while these during strong storms (Dstmin ≤ −100 nT) are generally lower than 90.0%, especially for the PPP-ARP of some stations located at low latitudes which are lower than 40.0%. The mechanism of PPP-ARP decrease under geomagnetic storms is mainly due to the cycle slips and even loss of lock of GNSS signals caused by the storms induced ionospheric disturbances and scintillations. In addition, different from many previous studies, we found that the CSRS-PPP with AR can achieve good positioning accuracy (3D RMS <0.2 m) even under strong geomagnetic storms.

Modeling a Carrington-scale Stellar Superflare and Coronal Mass Ejection from κ1Cet

Benjamin J. **Lynch**, Vladimir S. Airapetian, C. Richard DeVore, Maria D. Kazachenko, Teresa Lüftinger, Oleg Kochukhov, Lisa Rosén, William P. Abbett

ApJ **2019**
https://arxiv.org/pdf/1906.03189.pdf

Observations from the Kepler mission have revealed frequent superflares on young and active solar-like stars. Superflares result from the large-scale restructuring of stellar magnetic fields, and are associated with the eruption of coronal material (a coronal mass ejection, or CME) and energy release that can be orders of magnitude greater than those observed in the largest solar flares. These catastrophic events, if frequent, can significantly impact the potential habitability of terrestrial exoplanets through atmospheric erosion or intense radiation exposure at the surface. We present results from numerical modeling designed to understand how an eruptive superflare from a young solar-type star, κ1Cet, could occur and would impact its astrospheric environment. Our data-inspired, three-dimensional magnetohydrodynamic modeling shows that global-scale shear concentrated near the radial-field polarity inversion line can energize the closed-field stellar corona sufficiently to power a global, eruptive superflare that releases approximately the same energy as the extreme 1859 Carrington event from the Sun. We examine proxy measures of synthetic emission during the flare and estimate the observational signatures of our CME-driven shock, both of which could have extreme space-weather impacts on the habitability of any Earth-like exoplanets. We also speculate that the observed 1986 Robinson-Bopp superflare from κ1Cet was perhaps as extreme for that star as the Carrington flare was for the Sun.

On the Need to Automate Support for Quality Assessment Studies of Space Weather Models

P. **MacNeice**

Space Weather **Volume16, Issue11** Pages 1627-1634 **2018**
sci-hub.tw/10.1029/2018SW002039

Model quality assessment (QA) and, where possible, model validation are critical steps in the life cycle of models destined to play a role in space weather research and forecasting. A major goal of QA is to characterize the state of the art of models of a given class, for example, models of the global corona and solar wind. This requires consistent assessment of all major models in the class. Commonly, QA has been done in what amounts to campaign mode, generating reports that capture the quality of a particular model or a limited set of models for specific events or time intervals. Inconsistencies between study designs, the limited scope of each study, and the intermittency with which the study reports appear in the literature mean that we never achieve a complete assessment of the state of the art. In addition, the time frame in which new models appear or existing models are upgraded is comparable to the publication time of peer-reviewed validation reports, which means that these reports are often out of date soon after they are published. The community's current QA strategy is inadequate and unsustainable. In this paper we show why it is unsustainable and advocate for the development of automated protocols which can, with minimal ongoing labor cost, support the community's efforts to maintain up-to-date results. We illustrate the concept with results from a pilot scheme developed in conjunction with the Solar Heliospheric and Interplanetary Environment community.

The HESPERIA HORIZON 2020 Project and Book on Solar Particle Radiation Storms Forecasting and Analysis

Olga E. **Malandraki** , Norma B. Crosby

Space Weather Volume16, Issue6 June **2018** Pages 591-592
http://sci-hub.tw/https://onlinelibrary.wiley.com/doi/abs/10.1029/2018SW001950

This article presents the High Energy Solar Particle Events forecasting and Analysis (HESPERIA) project, supported by the HORIZON 2020 programme of the European Union (Project 637324) as well as the resultant recently published book entitled Solar Particle Radiation Storms Forecasting and Analysis, The HESPERIA HORIZON 2020 Project and Beyond, edited by Malandraki and Crosby, Springer, Astrophysics and Space Sciences Library, 2018, ISBN 978-3-319-60051-2. The book reviews the results of the HESPERIA project as well as our current understanding of solar energetic particle physics.

See https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/swq.18

Solar Energetic Particles and Space Weather: Science and Applications **Review**
Olga E. **Malandraki** and Norma B. Crosby
In: O.E. Malandraki, N.B. Crosby (eds.), Solar Particle Radiation Storms Forecasting and Analysis Chapter 1, **2018**
https://link.springer.com/content/pdf/10.1007%2F978-3-319-60051-2.pdf
File Malandraki_Crosby_SEPs_Forecasting and Analysis_Book.pdf
This chapter provides an overview on solar energetic particles (SEPs) and their association to space weather, both from the scientific as well as from the applications perspective. A historical overview is presented on how SEPs were discovered in the 1940s and how our understanding has increased and evolved since then. Current state-of-the-art based on unique measurements obtained in the 3-dimensional heliosphere (e.g. by the Ulysses, ACE, STEREO spacecraft) and their analysis is also presented. Key open questions on SEP research expected to be answered in view of future missions that will explore the solar corona and inner heliosphere are highlighted. This is followed by an introduction to why SEPs are studied, describing the risks that SEP events pose on technology and human health. Mitigation strategies for solar radiation storms as well as examples of current SEP forecasting systems are reviewed, in context of the two novel real-time SEP forecasting tools developed within the EU H2020 HESPERIA project.

Extreme Space Weather Impact: An Emergency Management Perspective
Mark H. **MacAlester*** andWilliam Murtagh
Space Weather, Volume 12, Issue 8, pp. 530-537 **2014**
http://onlinelibrary.wiley.com/doi/10.1002/SWQv11i003/pdf
In 2010, the Department of Homeland Security's Federal Emergency Management Agency (FEMA) partnered with the National Oceanic and Atmospheric Administration's Space Weather Prediction Center (SWPC) to investigate the potential for extreme space weather conditions to impact National Security/Emergency Preparedness communications—those communications vital to a functioning government and to emergency and disaster response—in the United States. Given the interdependencies of modern critical infrastructure, the initial systematic review of academic research on space weather effects on communications expanded to other critical infrastructure sectors, federal agencies, and private sector organizations. While the effort is ongoing, and despite uncertainties inherent with this hazard, FEMA and the SWPC did draw some conclusions. If electric power remains available, an extreme space weather event will result in the intermittent loss of HF and similar sky wave radio systems, minimal direct impact to public safety line-of-sight radio and commercial cellular services, a relatively small loss of satellite services as a percentage of the total satellite fleet, interference or intermittent loss of satellite communications and GPS navigation and timing signals, and no first-order impact to consumer electronic devices. Vulnerability of electric power to an extreme geomagnetic storm remains the primary concern from an emergency management perspective, but actual impact is not well understood at present. A discussion of potential impacts to infrastructure from the loss of electric power from any hazard is provided using the 2011 record tornado outbreak in Alabama as an example.

On the need to automate support for quality assessment studies of space weather models.
MacNeice, P.
(**2018**). Space Weather, 16, 1627–1634.
https://doi.org/10.1029/2018SW002039
Space Weather Quarterly Vol. 15, Issue 4, **2018**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/swq.20

Space Weather Magnetometer Aboard GEO-KOMPSAT-2A
W. **Magnes**, O. Hillenmaier, […] , C. H. Lee
Space Science Reviews volume 216, Article number: 119 (**2020**)
https://link.springer.com/content/pdf/10.1007/s11214-020-00742-2.pdf
https://link.springer.com/article/10.1007/s11214-020-00742-2
The South Korean meteorological and environmental satellite GEO-KOMPSAT-2A (GK-2A) was launched into geostationary orbit at 128.2∘ East on 4 December 2018. The space weather observation aboard GK-2A is performed by the Korea Space Environment Monitor. It consists of three particle detectors, a charging monitor and a four-sensor Service Oriented Spacecraft Magnetometer (SOSMAG).
The magnetometer design aims for avoiding strict magnetic cleanliness requirements for the hosting spacecraft and an automated on-board correction of the dynamic stray fields which are generated by the spacecraft. This is achieved through the use of two science grade fluxgate sensors on an approximately one meter long boom and two additional magnetoresistance sensors mounted within the spacecraft body.

This paper describes the instrument design, discusses the ground calibration methods and results, presents the post-launch correction and calibration achievements based on the data which were acquired during the first year in orbit and demonstrates the in-flight performance of SOSMAG with two science cases.
The dynamic stray fields from the GK-2A spacecraft, which was built without specific magnetic cleanliness considerations, are reduced up to a maximum factor of 35. The magnitude of the largest remnant field from an active spacecraft disturber is 2.0 nT. Due to a daily shadowing of the SOSMAG boom, sensor intrinsic offset oscillations with a periodicity up to 60 minutes and peak-to-peak values up to 5 nT remain in the corrected data product.
The comparison of the cleaned SOSMAG data with the Tsyganenko 2004 magnetic field model and the magnetic field data from the Magnetospheric Multiscale mission demonstrates that the offset error is less than the required 5 nT for all three components and that the drift of the offsets over 10 months is less than 7 nT.
Future work will include a further reduction of the remaining artefacts in the final data product with the focus on lessening the temperature driven sensor oscillations with an epoch based identification and correction. **11 May 2019, 8 August, 2019**

The Physical Processes of CME/ICME Evolution Review

Ward **Manchester** IV, Emilia K. J. Kilpua, Ying D. Liu, Noé Lugaz, Pete Riley, Tibor Török, Bojan Vršnak

Space Science Reviews Volume 212, Issue 3–4, pp 1159–1219 **2017**

https://link.springer.com/content/pdf/10.1007%2Fs11214-017-0394-0.pdf

As observed in Thomson-scattered white light, coronal mass ejections (CMEs) are manifest as large-scale expulsions of plasma magnetically driven from the corona in the most energetic eruptions from the Sun. It remains a tantalizing mystery as to how these erupting magnetic fields evolve to form the complex structures we observe in the solar wind at Earth. Here, we strive to provide a fresh perspective on the post-eruption and interplanetary evolution of CMEs, focusing on the physical processes that define the many complex interactions of the ejected plasma with its surroundings as it departs the corona and propagates through the heliosphere. We summarize the ways CMEs and their interplanetary CMEs (ICMEs) are rotated, reconfigured, deformed, deflected, decelerated and disguised during their journey through the solar wind. This study then leads to consideration of how structures originating in coronal eruptions can be connected to their far removed interplanetary counterparts. Given that ICMEs are the drivers of most geomagnetic storms (and the sole driver of extreme storms), this work provides a guide to the processes that must be considered in making space weather forecasts from remote observations of the corona. **17-18 Apr 1999, 14 July 2000, 27 May 2002, 28 October 2003, 2 November 2008, 12 December 2008, 16 June 2010, 7 Mar 2012**

The Varying Core Magnetic Field from a Space Weather Perspective Review

Mioara **Mandea,** Michael Purucker

Space Science Reviews February **2018**, 214:11

https://link.springer.com/content/pdf/10.1007%2Fs11214-017-0443-8.pdf

This paper summarizes recent advances in our understanding of geomagnetism, and its relevance to terrestrial space weather. It also discusses specific core magnetic field features such as the dipole moment decay, the evolution of the South Atlantic anomaly, and the location of the magnetic poles that are of importance for the practice of space weather.

International Collaboration Within the United Nations Committee on the Peaceful Uses of Outer Space: Framework for International Space Weather Services (2018–2030)

I. R. **Mann**, S. Di Pippo, H. J. Opgenoorth, M. Kuznetsova, D. J. Kendall

Space Weather Volume16, Issue5 May **2018** Pages 428-433

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2018SW001815

Severe space weather is a global threat that requires a coordinated global response. In this Commentary, we review some previous successful actions supporting international coordination between member states in the United Nations (UN) context and make recommendations for a future approach. Member states of the UN Committee on the Peaceful Uses of Outer Space (COPUOS) recently approved new guidelines related to space weather under actions for the long-term sustainability of outer space activities. This is to be followed by UN Conference on the Exploration and Peaceful Uses of Outer Space (UNISPACE)+50, which will take place in June 2018 on the occasion of the fiftieth anniversary of the first UNISPACE I held in Vienna in 1968. Expanded international coordination has been proposed within COPUOS under the UNISPACE+50 process, where priorities for 2018–2030 are to be defined under Thematic Priority 4: Framework for International Space Weather Services. The COPUOS expert group for space weather has proposed the creation of a new International Coordination Group for Space Weather be implemented as part of this thematic priority. This coordination group would lead international coordination between member states and across international stakeholders, monitor progress against implementation of guidelines and best practices, and promote coordinated global efforts in the space weather ecosystem spanning observations, research, modeling, and validation, with the goal of improved space weather services. We argue that such improved coordination at the international policy level is essential for increasing global resiliency against the threats arising from severe space weather.

Chapter 20 - Ionosphere and Thermosphere Responses to Extreme Geomagnetic Storms **Review**

Anthony J. **Mannucci** Bruce T.Tsurutani

In: Extreme Events in Geospace Origins, Predictability, and Consequences **2018**, Pages 493-511

http://sci-hub.tw/10.1016/B978-0-12-812700-1.00020-0

Past research on the ionospheric responses to geomagnetic storms provides valuable information on what can plausibly occur during extreme events. In this chapter, we focus on the phenomenon known as positive phase ionospheric storms, which tend to occur during the (geomagnetic) main storm phase. Positive phase refers to large daytime increases in the peak plasma density or column density (total electron content or TEC) over a period of at least 2–3 h. The TEC increase is the result of vertically convected plasma caused by E × B drift in the presence of a large east-west electric field of magnetospheric origin. Satellite data has revealed the broad hemispheric extent of the ionospheric changes that occur during daytime hours. Mid-to-low latitude TEC increases can be 5–10 times the quiet daytime values. Large TEC spatial gradients appear at middle latitudes, where the lower-latitude increases in TEC that are caused by uplifted plasma meet with high-velocity plasma caused by high-latitude electric fields. Another mid-latitude impact is a localized, large (> 60 TEC Units or 1016 el/m2) nighttime TEC enhancement feature following the positive phase storm, which was first observed over Florida following the October 30, 2003, storm. These large perturbations in the ionosphere are likely to have corollary effects on the thermosphere, in addition to the directly driven high-latitude thermospheric perturbations that are widely reported. We describe thermospheric impacts, including density increases and buoyancy waves, at altitudes above 500 km due to ion-neutral drag forces between the neutral species and the vertically uplifted plasma. These extremes in ionospheric behavior have consequences for a variety of technological systems.

Charting a Path Toward Improved Space Weather Forecasting

Mannucci, A. J.

Space Weather, Vol. 10, No. 7, S07003, **2012**

http://dx.doi.org/10.1029/2012SW000819

As the space weather community works toward a comprehensive "Sun-to-mud" forecasting capability, it is natural to expect challenging initial steps, similar to what occurred in terrestrial forecasting more than 50 years ago (Siscoe, 2006). This should not deter the implementation of first-principles-based forecasting for the upper atmosphere, magnetosphere, and ground-induced currents, augmented by data-driven methods where appropriate. Consider, for example, forecasting upper atmosphere disruptions following detection of a coronal mass ejection (CME) near the Sun. The community should seize the moment to establish an ambitious program of forecasting that takes advantage of the lead time available (usually 1-3 days) after a CME has been first detected. Forecasting geomagnetic storms due to high-speed streams is likely less challenging, with potentially longer lead times.

Current State of Reduced Solar Activity: Intense Space Weather Events in the Inner Heliosphere

P.K. **Manoharan**, K. Mahalakshmi, A. Johri, B.V. Jackson, D. Ravikumar,
K. Kalyanasundaram, S.P. Subramanian, A. K. Mittal

Sun and Geosphere, **2018**; 13/2: 135 -143

http://newserver.stil.bas.bg/SUNGEO//00SGArhiv/SG_v13_No2_2018-pp-135-143.pdf

We present a study of 21 geomagnetic storms, occurred during 2011–2017 in association with the propagation of coronal mass ejections (CMEs). These storms are selected with the minimum storm disturbance index (SYM-H) intensity of -100 nT or less and are distributed from the maximum to the minimum of the weak solar cycle 24. We identify and investigate these storm-driving CMEs (halo and partial halo CMEs) by combining EUV and white-light images in the nearSun region, interplanetary scintillation images in between the Sun and the Earth, and in-situ measurements at the nearEarth orbit. These CMEs cover a wide range of initial speeds, ~180 to 2680 km/s. For about 50% of the CMEs, the fast initial speed at the near-Sun region does not correlate with the final speed at the near-Earth orbit. The storm indexes range between -100 and -233 nT and they are associated with minimum Bz values in the range of -12 to -38 nT. The Forbush decrease (FD) levels associated with these storms vary in the range of about -2% to -10%. A comparison of travel times of CMEs to 1 AU with the observed initial/final speeds and estimated initial speed suggests that a large fraction of fast initial speeds could possibly be due to the sudden expansion of the CME into a relatively low pressure interplanetary medium. Most of the geomagnetic storms (i.e., 19 storms) have been caused by the strong intrinsic magnetic field of the CME and only 2 storms are produced by the sheath region between the arrival times of interplanetary shock and CME. The geomagnetic storm index is compared with the possible reconnection electric field component, BzVICME. It suggests an empirical relationship

for the likely lower level of storm index, SYM-H = -70 - 0.003·BzVICME. (nT), in which Bz and VICME are respectively given in units of nT and km/s. **21-23 June 2015**
Table 1 lists 21 intense geomagnetic events examined in this study

Predicting solar energetic proton events (E > 10 MeV)

Marlon Núñez

SPACE WEATHER, VOL. 9, S07003, 28 PP., **2011**

A high level of proton radiation exposure can be dangerous to astronauts, satellite equipment, and air passengers/crew flying along polar routes. The presented solar energetic proton (SEP) event forecaster is based on a dual-model approach for predicting the time interval within which the integral proton flux is expected to meet or surpass the Space Weather Prediction Center threshold of J (E > 10 MeV) = 10 pr cm−2 sr−1 s−1 and the intensity of the first hours of well- and poorly connected SEP events. This forecaster analyzes flare and near-Earth space environment data (soft X-ray, differential and integral proton fluxes). The purpose of the first model is to identify precursors of well-connected events by empirically estimating the magnetic connectivity from the associated CME/flare process zone to the near-Earth environment and identifying the flare temporally associated with the phenomenon. The goal of the second model is to identify precursors of poorly connected events by using a regression model that checks whether the differential proton flux behavior is similar to that in the beginning phases of previous historically poorly connected SEP events and thus deduce similar consequences. An additional module applies a higher-level analysis for inferring additional information about the situation by filtering out inconsistent preliminary forecasts and estimating the intensity of the first hours of the predicted SEP events. The high-level module periodically retrieves solar data and, in the case of well-connected events, automatically identifies the associated flare and active region. For the events of solar cycles 22 and 23 of the NOAA/SWPC SEP list, the presented dual-model system, called UMASEP, has a probability of detection of all well- and poorly connected events of 80.72% (134/166) and a false alarm rate of 33.99% (69/203), which outperforms current automatic forecasters in predicting >10 MeV SEP events. The presented forecaster has an average warning time of 5 h 10 min for the successfully predicted events, 1 h 5 min for well-connected events and 8 h 28 min for poorly connected events, with a maximum warning time of 24 h for very gradual SEP events.

Solar radio emission as a disturbance of aeronautical radionavigation

C. **Marqué**, K.-L. Klein, C. Monstein, H. Opgenoorth, A. Pulkkinen, S. Buchert, S. Krucker, R. Van Hoof, P. Thulesen

Journal of Space Weather and Space Climate (JSWSC), **8**, A42 **2018**

https://arxiv.org/pdf/1808.06878.pdf

On **November 4th 2015** secondary air traffic control radar was strongly disturbed in Sweden and some other European countries. The disturbances occurred when the radar antennas were pointing at the Sun. In this paper, we show that the disturbances coincided with the time of peaks of an exceptionally strong (∼105 Solar Flux Units) solar radio burst in a relatively narrow frequency range around 1~GHz.
This indicates that this radio burst is the most probable space weather candidate for explaining the radar disturbances. The dynamic radio spectrum shows that the high flux densities are not due to synchrotron emission of energetic electrons, but to coherent emission processes, which produce a large variety of rapidly varying short bursts (such as pulsations, fiber bursts, and zebra patterns). The radio burst occurs outside the impulsive phase of the associated flare, about 30 minutes after the soft X-ray peak, and it is temporarily associated with fast evolving activity occurring in strong solar magnetic fields. While the relationship with strong magnetic fields and the coherent spectral nature of the radio burst provide hints towards the physical processes which generate such disturbances, we have so far no means to forecast them. Well-calibrated monitoring instruments of whole Sun radio fluxes covering the UHF band could at least provide a real-time identification of the origin of such disturbances, which reports in the literature show to also affect GPS signal reception.

The impact of the November 4th 2015 event on air traffic radars

Christophe **Marque**_y1, Karl Ludwig Klein2, Christian Monstein3, Hermann Opgenoorth4, Stephan Buchert4, Antti Pulkkinen5, and S□am Krucker6

CESRA **2016**, p.81

http://cesra2016.sciencesconf.org/conference/cesra2016/pages/CESRA2016_prog_abs_book_v3.pdf

On November 4th 2015, NOAA AR 12443 produced a relatively modest M3.7 are associated with one of the strongest L-band radio burst since 2011. This event had a severe impact on ATC radars operated in Sweden, triggering the closure of the swedish airspace for a couple of hours. We will present here the ongoing e_ort to analyse this event and to explain why these radars were so severely a_ected.

Quantifying the performance of geomagnetically induced current models

S. **Marsal**, J.M. Torta

Space Weather **Volume17, Issue7** Pages 941-949 **2019**

sci-hub.se/10.1029/2019SW002208

We describe a metric that has been repeatedly applied to assess the performance of models aimed at predicting geomagnetically induced currents from Space Weather events. The used parameterization, based on the well-known root-mean-square error between model and observations, is simple and intuitive. Its use is exemplified, and its advantages and disadvantages are discussed, as well as its relationship with the widely extended correlation coefficient, r. Although the use of r alone is inappropriate for purposes of evaluating the agreement between model and observations, its use is recommended to complement the described performance parameter.

SPARX: a modelling system for Solar Energetic Particle Radiation Space Weather forecasting

M. S. **Marsh**, S. Dalla, M. Dierckxsens, T. Laitinen, N. B. Crosby

Space Weather, **2014**

http://arxiv.org/pdf/1409.6368v1.pdf

The capability to predict the parameters of an SEP event such as its onset, peak flux, and duration is critical to assessing any potential space weather impact. We present a new operational modelling system simulating the propagation of Solar Energetic Particles (SEPs) from locations near the Sun to any given location in the heliosphere. The model is based on the test particle approach and is spatially 3D, thus allowing for the possibility of transport in the direction perpendicular to the magnetic field. The model naturally includes the effects of perpendicular propagation due to drifts and drift-induced deceleration. The modelling framework and the way in which parameters of relevance for Space Weather are obtained within a forecasting context are described. The first results from the modelling system are presented. These results demonstrate that corotation and drift of SEP streams play an essential role in shaping SEP flux profiles.

Data Handling and Assimilation for Solar Event Prediction

Petrus C. **Martens**, Rafal A. Angryk

Space Weather of the Heliosphere: Processes and Forecasts Proceedings IAU Symposium No. 335, 2018 **2017**

https://arxiv.org/pdf/1712.01402.pdf

The prediction of solar flares, eruptions, and high energy particle storms is of great societal importance. The data mining approach to forecasting has been shown to be very promising. Benchmark datasets are a key element in the further development of data-driven forecasting. With one or more benchmark data sets established, judicious use of both the data themselves and the selection of prediction algorithms is key to developing a high quality and robust method for the prediction of geo-effective solar activity. We review here briefly the process of generating benchmark datasets and developing prediction algorithms.

Between heaven and earth: The legal challenges of human space travel

Masson-Zwaan, Tanja; Freeland, Steven

Acta Astronautica, Volume 66, Issue 11, p. 1597-1607. **2010**

sci-hub.tw/10.1016/j.actaastro.2009.12.015

Since the first space object was launched into orbit in 1957, humankind has been engaged in a constant effort to realise ever more ambitious plans for space travel. Probably the single most important element in this ongoing evolution is the development of technology capable of transporting large numbers of passengers into outer space on a commercial basis. Within the foreseeable future, space will no longer be the sole domain of professionally trained astronauts or the exceptionally wealthy.

The prospects for both suborbital and orbital private human access to space give rise to some interesting and difficult legal questions. It also opens up an exciting opportunity to develop an adequate system of legal regulation to deal with these activities. The existing international legal regimes covering air and space activities are not well suited to large-scale commercial access to space, largely because they were developed at a time when such activities were not a principal consideration in the mind of the drafters. The lack of legal clarity represents a major challenge and must be addressed as soon as possible, to provide for appropriate standards and further encourage (not discourage) such activities.

This article will examine some of the more pressing legal issues associated with the regulation of space transportation of passengers on a commercial basis, seen in the light of Article 1 of the Outer Space Treaty of 1967, which states that the 'exploration and use of outer space […] shall be carried out for the benefit and in the interests of all countries […] and shall be the province of all mankind'. An appropriate balance must be found between the commercial and technological opportunities that will arise and the principles upon which the development of international space law have thus far been based.

Radiation Exposure and Shielding Effects on the Lunar Surface
Daniel **Matthiä**, Thomas Berger
Space Weather Volume22, Issue12 December **2024** e2024SW004095
https://doi.org/10.1029/2024SW004095
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2024SW004095
The Moon will be a primary target for human space exploration in the near future. A limiting factor for a crewed mission to the Moon is the radiation dose during their stay on the lunar surface. While the total dose is expected to be dominated by the galactic cosmic radiation (GCR), the potential occurrence of large solar energetic particle events may lead to severe short-term effects and endanger the success of the mission. This work investigated the expected dose rates for maximum GCR intensity and the total dose from several historical solar energetic particle events, including the NASA reference event, through the application of numerical simulations with the Geant4 Monte-Carlo framework. An evaluation of the shielding effect of lunar regolith was carried out. For the solar particle events a shielding of more than 4 g/cm2 of regolith would reduce the expected dose to below the current 30-day limits and a shielding of more than 10 g/cm2 would result in a safety margin factor of two. For GCR adding additional mass shielding did not reduce the absorbed dose significantly. The estimated total dose equivalent received utilizing around 180 g/cm2 of regolith amounted to 200 mSv/year, which is only about 25% below the corresponding estimates for an unshielded environment. The comparison to model and experimental data from literature showed reasonable agreement to measurements but the analysis of various earlier model results revealed, that substantial differences between the models exist, despite all improvements that have been achieved in recent years.

The Solar Particle Event on 10–13 September 2017: Spectral Reconstruction and Calculation of the Radiation Exposure in Aviation and Space
Daniel **Matthiä**, Matthias M. Meier, Thomas Berger
Space Weather Volume16, Issue8 August **2018** Pages 977-986
http://sci-hub.tw/10.1029/2018SW001921
The solar energetic particle event on 10 September 2017 and on the following days was the strongest event in recent years. It was recorded as ground level enhancement 72 by neutron monitor stations on Earth and measured by a number of instruments in space. One aspect of such a space weather event is the potentially increased radiation exposure in aviation and space. Numerical simulations can help estimate the elevated dose rates during such an event; a critical aspect in these simulations is the description of the primary particle spectrum. In this work, we present 1-hr averaged proton spectra during the event derived from Geostationary Operational Environmental Satellite measurements and described by two different analytic functions. The derived proton spectra are used to calculate the radiation exposure in aviation and different space scenarios: low-Earth orbit, interplanetary space, and Mars surface, and the results are discussed in the context of available experimental data. While the results indicate that in most of these scenarios in aviation and space the event was of little significance compared to the total exposure from galactic cosmic radiation, the skin dose in a lightly shielded environment in interplanetary space may have reached about 30% to 60% of the NASA 30-day dose limit.

Economic impact and effectiveness of radiation protection measures in aviation during a ground level enhancement
Daniel **Matthiä**1*, Martin Schaefer2 and Matthias M. Meier
J. Space Weather Space Clim., 5, A17 (**2015**)
http://www.swsc-journal.org/articles/swsc/pdf/2015/01/swsc140044.pdf
In addition to the omnipresent irradiation from galactic cosmic rays (GCR) and their secondary products, passengers and aircraft crew may be exposed to radiation from solar cosmic rays during ground level enhancements (GLE). In general, lowering the flight altitude and changing the flight route to lower latitudes are procedures applicable to immediately reduce the radiation exposure at aviation altitudes. In practice, however, taking such action necessarily leads to modifications in the flight plan and the consequential, additional fuel consumption constrains the mitigating measures.
In this work we investigate in a case study of the ground level event of **December 13th 2006** how potential mitigation procedures affect the total radiation exposure during a transatlantic flight from Seattle to Cologne taking into account constraints concerning fuel consumption and range.

The physics of cosmic rays applied to space weather **Review**
H. **Mavromichalaki**
Advances in Solar and Solar-Terrestrial Physics, 135-161, ***2012***
http://cosray.phys.uoa.gr/publications/D95.pdf
This report summarizes the efforts of the cosmic ray community to establish an Alert signal for dangerous particle fluxes heading to the Earth using the worldwide neutron monitor network, as well as to implement various

algorithms on phenomena as Ground Level Enhancements, variations of cosmic ray gradient and anisotropy and to successfully measure radiation doses on spacecrafts and aircrafts.

Real-time predictions of geomagnetic storms and substorms: Use of the Solar Wind Magnetosphere-Ionosphere System model

Mays, M. L.; Horton, W.; Spencer, E.; Kozyra, J.
Space Weather, Vol. 7, No. 7, S07001, 2009
http://dx.doi.org/10.1029/2008SW000459

A low-dimensional, plasma physics-based, nonlinear dynamical model of the coupled magnetosphere-ionosphere system, called Real-Time Solar Wind Magnetosphere-Ionosphere System (WINDMI), is used **to predict *AL* and *Dst* values approximately 1 h before geomagnetic substorm and storm event.** Subsequently, every 10 min ground-based measurements compiled by World Data Center, Kyoto, are compared with model predictions (http://orion.ph.utexas.edu/~windmi/realtime/). WINDMI model runs are also available at the Community Coordinated Modeling Center (http://ccmc.gsfc.nasa.gov/). The performance of the Real-Time WINDMI model is quantitatively evaluated for 22 storm/substorm event predictions from February 2006 to August 2008. Three possible input solar wind-magnetosphere coupling functions are considered: the standard rectified coupling function, a function due to Siscoe, and a recent function due to Newell. Model *AL* and *Dst* predictions are validated using the average relative variance (ARV), correlation coefficient (COR), and root mean squared error (RMSE). The Newell input function yielded the best model *AL* predictions by all three measures (mean ARV, COR, and RMSE), followed by the rectified, then Siscoe input functions. Model *AL* predictions correlate at least 1 standard deviation better with the *AL* index data than a direct correlation between the input coupling functions and the *AL* index. The mean *Dst* ARV results show better prediction performance for the rectified input than the Siscoe and Newell inputs. The mean *Dst* COR and RMSE measures do not readily distinguish between the three input coupling functions.

Space Weather research in the Digital Age and across the full data lifecycle: Introduction to the Topical Issue

Ryan M. **McGranaghan**, Enrico Camporeale, Manolis Georgoulis and Anastasios Anastasiadis
J. Space Weather Space Clim. **2021**, 11, 50
https://www.swsc-journal.org/articles/swsc/pdf/2021/01/swsc210064.pdf
https://doi.org/10.1051/swsc/2021037

The onset and rapid advance of the Digital Age have brought challenges and opportunities for scientific research characterized by a continuously evolving data landscape reflected in the four V's of big data: volume, variety, veracity, and velocity. The big data landscape supersedes traditional means of storage, processing, management, and exploration, and requires adaptation and innovation across the full data lifecycle (i.e., collection, storage and processing, analytics, and representation). The Topical Issue, "Space Weather research in the Digital Age and across the full data lifecycle", collects research from across the full data lifecycle (collection, management, analysis, and communication; collectively "Data Science") and offers a tractable compendium that illustrates the latest computational and data science trends, tools, and advances for Space Weather research. We introduce the paradigm shift in Space Weather and the articles in the Topical Issue. We create a network view of the research that highlights the contribution to the change of paradigm and reveals the trends that will guide it hereafter.

The effects of solar radio bursts on frequency bands utilised by the aviation industry in Sub-Saharan Africa

Sarah Ruth **McKee**1*, Pierre Johannes Cilliers1, Stefan Lotz1 and Christian Monstein2
J. Space Weather Space Clim., 13 (**2023**) 4
https://www.swsc-journal.org/articles/swsc/pdf/2023/01/swsc210085.pdf

Solar radio bursts have been associated with a number of disruptions in avionic systems. The objective of this work is to develop solar radio burst interference thresholds which account for the technical specifications of aviation-related instrumentation, instrument operating frequencies as well as industry stipulated error tolerances. Solar radio bursts are suggested to be potentially hazardous when exceeding these calculated thresholds. Particular attention is paid to the radio altimeter, an important component in aviation safety. The thresholds suggested in this work for VHF communication, GPS navigation receivers and radio altimeter frequencies are; 102, 103, and 104 sfu respectively. Solar radio burst interference (for solar radio bursts above 104 sfu) is shown to result in large errors (64–251 m) in the altitude estimates for the Frequency Modulated Continuous Waves (FMCW) radio altimeter simulated in this work.

Workshop Addresses Aviation Community

Meehan, Jennifer; Kunches, Joseph
Space Weather, Vol. 10, No. 8, S08011, **2012**

Discussions focus on increasing awareness, education of space weather for the industry and providing better services for it

Understanding Space Weather Customers in GPS-Reliant Industries

Meehan, Jennifer; Fisher, Genene; Murtagh, William

Space Weather, Vol. 8, No. 6, S06003, **2010**

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2009SW000556

Since the last solar maximum, society has become extremely reliant on the Global Positioning System (GPS), which is often referred to as the "fourth utility" behind electricity, water, and natural gas. As the economy depends more and more on positioning, navigation, and timing, society's vulnerability to space weather continues to increase because space weather can be a significant cause of GPS errors. Critical applications such as railway control, highway traffic management, precision agriculture, emergency response, commercial aviation, and marine navigation all require GPS services. With such widespread and critical usage, industries are becoming more aware of how space weather can affect GPS signals, rapidly increasing the number of customers interested in real-time space weather products and services.

First Steps Toward the Verification of Models for the Assessment of the Radiation Exposure at Aviation Altitudes During Quiet Space Weather Conditions

Matthias M. **Meier** , Kyle Copeland, Daniel Matthiä, Christopher J. Mertens, Kai Schennetten

Space Weather Volume16, Issue9 September **2018** Pages 1269-1276

Space Weather Quarterly 15 No. 3 **2018**

sci-hub.tw/10.1029/2018SW001984

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/swq.19

Space weather is an important driver of the exposure of aircrew and passengers to cosmic rays at flight altitudes, which has been a matter of concern for several decades. The assessment of the corresponding radiation doses can be realized by measurements or model calculations that cover the whole range of the radiation field in terms of geomagnetic shielding, atmospheric shielding, and the effects of space weather. Since the radiation field at aviation altitudes is very complex in terms of particle composition and energy distribution, the accurate experimental determination of doses at aviation altitudes is still a challenging task. Accordingly, the amount of data with comparatively small uncertainties is scarce. The Community Coordinated Modeling Center invited the Federal Aviation Administration, the German Aerospace Center, and the National Aeronautics and Space Administration to make their radiation models for aviation CARI-7A, PANDOCA, and NAIRAS available for interested users via the Community Coordinated Modeling Center web site. A concomitant comparison of model calculations with measuring data provided information on the predicting capabilities and the uncertainties of the current versions of these models under quiet space weather conditions.

A space weather index for the radiation field at aviation altitudes

Matthias M. **Meier*** and Daniel Matthiä

J. Space Weather Space Clim. 4 (**2014**) A13

The additional dose contribution to the radiation exposure at aviation altitudes during Solar Particle Events (SPEs) has been a matter of concern for many years. After the Halloween storms in 2003 several airlines began to implement mitigation measures such as rerouting and lowering flight altitudes in response to alerts on the NOAA S-scale regarding solar radiation storms. These alerts are based on the integral proton flux above 10 MeV measured aboard the corresponding GOES-satellite which is operated outside the Earth's atmosphere in a geosynchronous orbit. This integral proton flux has, however, been proved to be an insufficient parameter to apply to the radiation field at aviation altitudes without an accompanying analysis of the shape of the energy spectrum. Consequently, false alarms and corresponding disproportionate reactions ensued. Since mitigating measures can be quite cost-intensive, there has been a demand for appropriate space weather information among responsible airline managers for about a decade. Against this background, we propose the introduction of a new Space Weather index D, based on dose rates at aviation altitudes produced by solar protons during solar radiation storms, as the relevant parameter for the assessment of corresponding radiation exposure. The Space Weather index D is a natural number given by a graduated table of ranges of dose rates in ascending order which is derived by an equation depending on the dose rate of solar protons.

Flares at Earth and Mars: An Ionospheric Escape Mechanism?

M. **Mendillo**, P. J. Erickson, S.-R. Zhang , M. Mayyasi, C. Narvaez, E. Thiemann, P. Chamberlain, L. Andersson, W. Peterson

Space Weather Volume16, Issue8 August **2018** Pages 1042-1056 http://sci-hub.tw/10.1029/2018SW001872

Solar flares are nature's active experiment upon a planet's upper atmosphere and ionosphere. Observed effects at Earth are consistent with a “second sunrise” scenario that produces changes in electron density, electron temperature, and plasma dynamics. A solar active region in September 2017 provoked ionospheric disturbances due to solar flares observed at Earth (**6 September**) and later at Mars (**10 and 17 September**). Incoherent scatter radar observations from the Millstone Hill Observatory showed a burst of upward diffusion due to electron temperature enhancements. We explore the companion possibility of flares causing upward drifts and plasma escape at Mars. Solar observations made by the EUV Monitor instrument on the Mars Atmosphere and Volatile EvolutioN (MAVEN) satellite are used to portray the time histories of irradiance changes to determine the “early” (onset to peak emission) and “late” (decay to background) time scales for these flares. During the initial phase of a flare (when photons ionize an atmosphere unmodified by flare heating), MAVEN was well above the ionosphere and thus no in situ data are available to asses this period of possible plasma escape. Estimates made using a simple terrestrial model for plasma drifts in the topside ionosphere suggest that escape rates can be enhanced at Mars at “early” times. The “late time” effects observed below 400 km 2 hr after the flare onset times did not reveal conclusive remnants of the proposed mechanism. No model of the Martian thermosphere-ionosphere system has produced a self-consistent simulation of solar flare effects upon Mars' upper atmosphere and ionosphere.

Thermosphere-Ionosphere Modeling With Forecastable Inputs: Case Study of the June 2012 High Speed Stream Geomagnetic Storm

Xing **Meng**, Anthony J. Mannucci, Olga P. Verkhoglyadova, Bruce T. Tsurutani, Aaron J. Ridley, Ja-Soon Shim

Space Weather **2020**

https://doi.org/10.1029/2019SW002352

Forecasting conditions in the thermosphere and ionosphere is a key outcome expected from space weather research. In this work, we perform numerical simulations using the first-principles models Global Ionosphere Thermosphere Model (GITM) and Thermosphere Ionosphere Electrodynamics General Circulation Model (TIE-GCM) to address the reliability of thermospheric-ionospheric forecasts. When considering forecasts applicable to periods of geomagnetic activity, careful consideration is required of model inputs, which largely determine how the models will simulate disturbed conditions. We adopt an approach to drive the models with solar wind parameters and the 10.7 cm solar radio flux. This aligns our investigation with recent research and operational activities to forecast solar wind conditions at the Earth a few days in advance. In this work, we examine a weak geomagnetic storm, the June 2012 high-speed-stream event, for which we drive GITM and TIE-GCM with observed solar wind and F10.7 values. We find general agreement between the simulations and observation-based Global Ionospheric Maps of the total electron content (TEC) response. However, overestimated TEC response is found in the middle-low latitudinal region of the American sector and surrounding areas for both GITM and TIE-GCM during similar time periods. By conducting numerical modeling experiments and comparing the modeling results with observational data, we find that the overestimated TEC response can be almost equally attributed to the solar wind driving and F10.7 driving during the June 2012 event. We conclude that the accuracy of the high-latitude electric field and the solar irradiance are crucial to reproduce the TEC response in forecastable-mode modeling.

Extreme Relativistic Electron Fluxes in GPS Orbit: Analysis of NS41 BDD-IIR Data

Nigel P. **Meredith**, Thomas E. Cayton, Michael D. Cayton, Richard B. Horne

Space Weather Volume21, Issue6 June **2023** e2023SW003436

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https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2023SW003436

Relativistic electrons in the Earth's outer radiation belt are a significant space weather hazard. Satellites in GPS-type orbits pass through the heart of the outer radiation belt where they may be exposed to large fluxes of relativistic electrons. In this study we conduct an extreme value analysis of the daily average relativistic electron flux in Global Positioning System orbit as a function of energy and L using data from the US NS41 satellite from 10 December 2000 to 25 July 2020. The 1 in 10 year flux at L = 4.5, in the heart of the outer radiation belt, decreases with increasing energy ranging from 8.2 × 106 cm−2s−1sr−1 MeV−1 at E = 0.6 MeV to 33 cm−2s−1sr−1 MeV−1 at E = 8.0 MeV. The 1 in 100 year is a factor of 1.1–1.7 larger than the corresponding 1 in 10 year event. The 1 in 10 year flux at L = 6.5, on field lines which map to the vicinity of geostationary orbit, decrease with increasing energy ranging from 6.2 × 105 cm−2s−1sr−1 MeV−1 at E = 0.6 MeV to 0.48 cm−2s−1sr−1 MeV−1 at E = 8.0 MeV. Here, the 1 in 100 year event is a factor of 1.1–13 times larger than the corresponding 1 in 10 year event, with the value of the factor increasing with increasing energy. Our analysis suggests that the fluxes of relativistic electrons with energies in the range 0.6 ≤ E ≤ 2.0 MeV in the region 4.25 ≤ L ≤ 4.75 have an upper bound. In contrast, further out and at higher energies the fluxes of relativistic electrons are largely unbounded.

COUPLING OF CORONAL AND HELIOSPHERIC MAGNETOHYDRODYNAMIC MODELS: SOLUTION COMPARISONS AND VERIFICATION

V. G. **Merkin**1, R. Lionello2, J. G. Lyon3, J. Linker2, T. Török2, and C. Downs2

2016 ApJ 831 23

Two well-established magnetohydrodynamic (MHD) codes are coupled to model the solar corona and the inner heliosphere. The corona is simulated using the MHD algorithm outside a sphere (MAS) model. The Lyon–Fedder–Mobarry (LFM) model is used in the heliosphere. The interface between the models is placed in a spherical shell above the critical point and allows both models to work in either a rotating or an inertial frame. Numerical tests are presented examining the coupled model solutions from 20 to 50 solar radii. The heliospheric simulations are run with both LFM and the MAS extension into the heliosphere, and use the same polytropic coronal MAS solutions as the inner boundary condition. The coronal simulations are performed for idealized magnetic configurations, with an out-of-equilibrium flux rope inserted into an axisymmetric background, with and without including the solar rotation. The temporal evolution at the inner boundary of the LFM and MAS solutions is shown to be nearly identical, as are the steady-state background solutions, prior to the insertion of the flux rope. However, after the coronal mass ejection has propagated through the significant portion of the simulation domain, the heliospheric solutions diverge. Additional simulations with different resolution are then performed and show that the MAS heliospheric solutions approach those of LFM when run with progressively higher resolution. Following these detailed tests, a more realistic simulation driven by the thermodynamic coronal MAS is presented, which includes solar rotation and an azimuthally asymmetric background and extends to the Earth's orbit.

Predicting magnetospheric dynamics with a coupled Sun-to-Earth model: Challenges and first results

V. G. **Merkin**, M. J. Owens, H. E. Spence, W. J. Hughes, J. M. Quinn

SPACE WEATHER, VOL. 5, S12001, doi:10.1029/2007SW000335, **2007**

Results from the first Sun-to-Earth coupled numerical model developed at the Center for Integrated Space Weather Modeling are presented. The model simulates physical processes occurring in space spanning from the corona of the Sun to the Earth's ionosphere, and it represents the first step toward creating a physics-based numerical tool for predicting space weather conditions in the near-Earth environment. Two 6- to 7-d intervals, representing different heliospheric conditions in terms of the three-dimensional configuration of the heliospheric current sheet, are chosen for simulations. These conditions lead to drastically different responses of the simulated magnetosphere-ionosphere system, emphasizing, on the one hand, challenges one encounters in building such forecasting tools, and on the other hand, emphasizing successes that can already be achieved even at this initial stage of Sun-to-Earth modeling.

Characterization of Solar Energetic Particle Radiation Dose to Astronaut Crew on Deep-Space Exploration Missions

Christopher J. **Mertens**, Tony C. Slaba

Space Weather **2019**

https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2019SW002363

Human radiation exposure from solar energetic particle (SEP) events during deep-space exploration missions has a greater impact on mission planning and operations compared to spaceflight missions to low Earth orbit. Deep-space SEP radiation exposure may require in-flight preventative actions in order to reduce the radiation risks to as low as reasonably achievable, to limit the onset and severity of acute biological responses, and to ensure that astronaut permissible exposure limits are not exceeded. In this paper, radiation dose to the blood forming organs (BFO) of astronaut crew are calculated from a set of historical SEP events, using the design of the Orion Multi-Purpose Crew Vehicle (MPCV). The BFO doses from the historical events are analyzed in several ways. The results show the range and upper limit of BFO doses expected in heavily shielded space vehicles such as the Orion MPCV, based on calculations from all the major SEP events encountered in the space age. The dose reduction properties of the MPCV storm-shelter are characterized over the broad range of SEP events included in the historical database. Correlations are derived between the integral proton fluence and BFO dose in the vehicle, showing that integral fluence is a good proxy for predicting or forecasting vehicle BFO dose. The best correlation with MPCV BFO dose is from the >100 MeV integral fluence. These results will assist in the design of future space weather architectures by identifying models and measurements needed to expand and extend NASA's existing SEP radiation risk tools in the support and management of human space exploration missions.

Geomagnetic influence on aircraft radiation exposure during a solar energetic particle event in October 2003

Mertens, Christopher J.; Kress, Brian T.; Wiltberger, Michael; Blattnig, Steve R.; Slaba, Tony S.; Solomon, Stanley C.; Engel, M.

Space Weather, Vol. 8, No. 3, S03006, **2010**
http://dx.doi.org/10.1029/2009SW000487
We present initial results from the Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) model during the Halloween 2003 superstorm. The objective of NAIRAS is to produce global, real-time, data-driven predictions of ionizing radiation for archiving and assessing the biologically harmful radiation exposure levels at commercial airline altitudes. We have conducted a case study of radiation exposure during a high-energy solar energetic particle (SEP) event in October 2003. The purpose of the case study is to quantify the important influences of the storm time and quiet time magnetospheric magnetic field on high-latitude SEP atmospheric radiation exposure. The Halloween 2003 superstorm is an ideal event to study magnetospheric influences on atmospheric radiation exposure since this event was accompanied by a major magnetic storm which was one of the largest of solar cycle 23. We find that neglecting geomagnetic storm effects during SEP events can underestimate the high-latitude radiation exposure from nearly 15% to over a factor of 2, depending on the flight path relative to the magnetosphere open-closed boundary.

SolarWeather Event Modelling and Prediction

Mauro **Messerotti** · Francesca Zuccarello · Salvatore L. Guglielmino · Volker Bothmer · Jean Lilensten · Giancarlo Noci · Marisa Storini · Henrik Lundstedt

Space Sci Rev, **2009; File**

Key drivers of solar weather and mid-term solar weather are reviewed by considering a selection of relevant physics- and statistics-based scientific models as well as a selection of related prediction models, in order to provide an updated operational scenario for space weather applications. The characteristics and outcomes of the considered scientific and prediction models indicate that they only partially cope with the complex nature of solar activity for the lack of a detailed knowledge of the underlying physics. This is indicated by the fact that, on one hand, scientific models based on chaos theory and non-linear dynamics reproduce better the observed features, and, on the other hand, that prediction models based on statistics and artificial neural networks perform better. To date, the solar weather prediction success at most time and spatial scales is far from being satisfactory, but the forthcoming ground- and space-based high-resolution observations can add fundamental tiles to the modelling and predicting frameworks as well as the application of advanced mathematical approaches in the analysis of diachronic solar observations, that are a must to provide comprehensive and homogeneous data sets.

Solar cycle variations of GPS amplitude scintillation for the polar region

K. **Meziane** , A. Kashcheyev, S. Patra , P. T. Jayachandran , A. M. Hamza

Space Weather e2019SW002434 **2020**

sci-hub.tw/10.1029/2019SW002434

Global Positioning System (GPS) L1 amplitude data, obtained using the Canadian High Arctic Ionospheric Network (CHAIN) during the period 2008-2018, is used to study the seasonal and solar cycle dependence of high latitude amplitude scintillation. The occurrence of amplitude scintillation is predominantly confined to the 10-18 Magnetic Local Time (MLT) and 72°-87° Altitude-Adjusted Corrected Geo-Magnetic (AACGM) sector, and is a winter and equinoctial phenomenon. The occurrence of amplitude scintillation shows a clear seasonal and solar cycle dependence with a maximum value of ~11% during the high solar activity early winter periods, and a secondary maximum in equinoctial months, and almost no occurrence during summer months. This pattern in occurrence suggests that amplitude scintillation is a phenomenon that is closely associated with the presence of patches and particle precipitation events.

Domain of Influence analysis: implications for Data Assimilation in space weather forecasting **Review**

Dimitrios **Millas**, Maria Elena Innocenti, Brecht Laperre, Joachim Raeder, Stefaan Poedts, Giovanni Lapenta

Frontiers in Astronomy and Space Sciences 7:571286 **2020**

https://arxiv.org/pdf/2009.04211.pdf
https://www.frontiersin.org/articles/10.3389/fspas.2020.571286/full
https://doi.org/10.3389/fspas.2020.571286

Solar activity, ranging from the background solar wind to energetic coronal mass ejections (CMEs), is the main driver of the conditions in the interplanetary space and in the terrestrial space environment, known as space weather. A better understanding of the Sun-Earth connection carries enormous potential to mitigate negative space weather effects with economic and social benefits. Effective space weather forecasting relies on data and models. In this paper, we discuss some of the most used space weather models, and propose suitable locations for data gathering with space weather purposes. We report on the application of \textit{Representer analysis (RA)} and \textit{Domain of Influence (DOI) analysis} to three models simulating different stages of the Sun-Earth connection: the OpenGGCM and Tsyganenko models, focusing on solar wind - magnetosphere interaction, and the PLUTO model, used to simulate CME propagation in interplanetary space. Our analysis is promising for space weather purposes for several reasons. First, we obtain quantitative information about the most useful locations of observation points, such as solar wind monitors. For example, we find that the absolute values of the DOI are extremely low in the magnetospheric plasma sheet. Since knowledge of that particular sub-system is crucial for space weather, enhanced monitoring of the region would be most beneficial. Second, we are able to better characterize the models. Although the current analysis focuses on spatial rather than temporal correlations, we find that time-independent models are less useful for Data Assimilation activities than time-dependent models. Third, we take the first steps towards the ambitious goal of identifying the most relevant heliospheric parameters for modelling CME propagation in the heliosphere, their arrival time, and their geoeffectiveness at Earth.

An operational software tool for the analysis of coronagraph images: Determining CME parameters for input into the WSA-Enlil heliospheric model

G. **Millward**1,2,*, D. Biesecker, 2, V. Pizzo, C. A. de Koning

Space Weather, Volume 11, Issue 2, pages 57–68, February **2013**

Coronal mass ejections (CMEs)—massive explosions of dense plasma that originate in the lower solar atmosphere and propagate outward into the solar wind—are the leading cause of significant space weather effects within Earth's environment. Computational models of the heliosphere such as WSA-Enlil offer the possibility of predicting whether a given CME will become geo-effective and, if so, the likely time of arrival at Earth. To be meaningful, such a forecast model is dependent upon accurately characterizing key parameters for the CME, notably its speed and direction of propagation, and its angular width. Studies by Zhao et al. (2002) and Xie et al. (2004) suggest that these key CME parameters can be deduced from geometric analysis of the elliptical “halo” forms observed in coronagraph images on spacecraft such as the Solar and Heliospheric Observatory (SOHO) and which result from a CME whose propagation is roughly toward or away from the observer. Both studies assume that the CME presents a circular cross-section and maintains a constant angular width during its radial expansion, the so called “cone model.” Development work at the NOAA Space Weather Prediction Center (SWPC) has been concerned with building and testing software tools to allow forecasters to determine these CME parameters routinely within an operational context, a key aspect of transitioning the WSA-Enlil heliospheric model into operations at the National Weather Service. We find “single viewpoint” cone analysis, while a useful start, to be highly problematic in many real-world situations. In particular, it is extremely difficult to establish objectively the correct ellipse that should be applied to a given halo form and that small changes in the exact ellipse chosen can lead to large differences in the deduced CME parameters. The inaccuracies in the technique are particularly evident for analysis of the “nearly circular” elliptical forms which result from CMEs that are propagating directly toward the observer and are therefore the most likely to be geo-effective. In working to resolve this issue we have developed a new three-dimensional (3-D) graphics-based analysis system which seeks to reduce inaccuracies by analyzing a CME using coronagraph images taken concurrently by SOHO and also by the two Solar TErrestrial RElations Observatory (STEREO) spacecraft, which provide additional viewing locations well away from the Sun-Earth line. The resulting “three view” technique has led to the development of the CME Analysis Tool (CAT), an operational software system in routine use at the SWPC as the primary means to determine CME parameters for input into the WSA-Enlil model. Results from the operational WSA-Enlil system are presented: utilizing CAT to provide CME input parameters, we show that, during the first year of operations at SWPC, the WSA-Enlil model has forecasted the arrival of CMEs at Earth with an average error 7.5 h.

Online Multi-step Ahead Prediction of Time-Varying Solar and Geomagnetic Activity Indices via Adaptive Neurofuzzy Modeling and Recursive Spectral Analysis

Masoud **Mirmomeni**, Caro Lucas, Babak Nadjar Araabi, Behzad Moshiri and Mohammad Reza Bidar

Solar Physics, Volume 272, Number 1, 189-213, **2011**

The time-varying Sun as the main source of space weather affects the Earth’s magnetosphere by emitting hot magnetized plasma in the form of solar wind into interplanetary space. Solar and geomagnetic activity indices and their chaotic characteristics vary abruptly during solar and geomagnetic storms. This variation depicts the difficulties in modeling and long-term prediction of solar and geomagnetic storms. On the other hand, the combination of neurofuzzy models and spectral analysis has been a subject of interest due to their many practical applications in modeling and predicting complex phenomena. However, these approaches should be trained by algorithms that need to be carried out by an offline data set, which influences their performance in online modeling and prediction of time-varying phenomena. This paper proposes an adaptive approach for multi-step ahead prediction of space weather indices by extending the regular singular spectrum analysis and locally linear neurofuzzy models to adaptive approaches. The combination of these recursive approaches fulfills requirements of long-term prediction of solar and geomagnetic activity indices. The results demonstrate the power of the proposed method in online prediction of space weather indices.

Energetic Particle Influence on the Earth's Atmosphere Review

Irina A. **Mironova** , Karen L. Aplin, Frank Arnold, Galina A. Bazilevskaya, R. Giles Harrison, Alexei A. Krivolutsky, Keri A. Nicoll, Eugene V. Rozanov, Esa Turunen and 1 more

Space Science Reviews November **2015**, Volume 194, Issue 1, pp 1-96

This manuscript gives an up-to-date and comprehensive overview of the effects of energetic particle precipitation (EPP) onto the whole atmosphere, from the lower thermosphere/mesosphere through the stratosphere and troposphere, to the surface. The paper summarizes the different sources and energies of particles, principally galactic cosmic rays (GCRs), solar energetic particles (SEPs) and energetic electron precipitation (EEP). All the proposed mechanisms by which EPP can affect the atmosphere are discussed, including chemical changes in the upper atmosphere and lower thermosphere, chemistry-dynamics feedbacks, the global electric circuit and cloud formation. The role of energetic particles in Earth's atmosphere is a multi-disciplinary problem that requires expertise from a range of scientific backgrounds. To assist with this synergy, summary tables are provided, which are intended to evaluate the level of current knowledge of the effects of energetic particles on processes in the entire atmosphere.

Retrospective analysis of GLEs and estimates of radiation risks Review

Leonty I. **Miroshnichenko**

J. Space Weather Space Clim. **2018**, 8, A52

https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc170020.pdf

28 February 2017 marked 75 years since the first confident registration of solar cosmic rays (SCRs), i.e., accelerated solar particles with energies from about 106 to ~1010 ÷ 1011 eV. Modern state of the problems related to the studies of Ground Level Enhancements (GLEs) of relativistic SCRs is critically analyzed based on available direct and proxy data. We are also taking into account extremely large fluxes of non-relativistic solar energetic particles (SEPs). Both kinds of SCR events are of great astrophysical and geo-scientific (geophysical) interests. A number of the GLE properties (total statistics, occurrence rate, longitude distribution, ranking of GLEs, a number of specific GLEs – so-called "rogue" SEP events etc.) are discussed in some detail. We note also the problems of GLE identification (definition) by ground-based observations, the difficulties in the studies of weak ("hidden", or sub-) GLEs etc. One of serious challenges to the problem of radiation hazard in space is a lack of a clear, unambiguous relation between the fluxes (fluences) of relativistic SCR and non-relativistic SEPs. Special attention is paid to the recent debate on the validity, origin and properties of the "ancient" events AD775, AD994, AD1859 (Carrington event) and BC3372. We demonstrate that, in spite of existing uncertainties in proton fluences above 30 MeV, all of them are fitted well by a unique distribution function, at least, with the present level of solar activity. Extremely large SEP events are shown to obey a probabilistic distribution on their fluences with a sharp break in the range of large fluences (or low probabilities). The studies of this kind may be extended for periods with different levels of solar activity in the past and/or in the future. Dose rates at aircraft altitudes are also demonstrated during some GLEs. Several examples of using the SCR data and GLE properties in radiation prediction schemes are considered.

Extreme solar particle event of 774 AD: reference as the worst-case scenario for space weather

Alexander **Mishev**,*a*,*b*,∗ Ilya Usoskin*a*,*b* and Sanja Panovska

ICRC2023 **2023**

https://pos.sissa.it/444/1229/pdf

Violent eruptive processes on the Sun can lead to an acceleration of solar energetic particles, which accordingly result in notable space weather effects, specifically an increase of the complex radiation field at aviation altitudes. A specific class represents events observed by ground-based detectors such as neutron monitors (NMs), the ground-level enhancements (GLEs). Here, we considered for study a specific event, namely the strongest known, yet not directly observed, that is the extreme solar particle event of 774 AD discovered on the basis of cosmogenic-isotopes measurements. After a convenient scaling of a GLE # 5 and employing the corresponding radiation model we computed the ambient dose at aviation altitudes during the 774 AD event. Since the spectrum of solar protons during 774 AD can not be directly obtained, as a first step we derived the spectra of the solar protons during the GLE # 5, the strongest directly observed by NM measurements. The GLE # 5 is assumed as a conservative approach because of the hardest derived spectra. The global map of the ambient dose was computed under realistic reconstruction of the geomagnetic field during the 774 AD epoch, obtained on the basis of archeo-paleomagnetic measurements. We show that the 774 AD event represents a significant space weather threat and can be used as a reference for the worst-case scenario for radiation dose received during GLEs at aviation altitudes.

Preface to measurement, specification and forecasting of the Solar Energetic Particle (SEP) environment and Ground Level Enhancements (GLEs) Review

Alexander **Mishev**1,2* and Piers Jiggens3

J. Space Weather Space Clim. **2019**, 9, E1

https://www.swsc-journal.org/articles/swsc/pdf/2019/01/swsc180076.pdf
The Sun emits energetic particles following eruptive events such as solar flares and Coronal Mass Ejections (CMEs). Solar Energetic Particles (SEPs) arrive in bursts known as Solar Particle Events (SPEs), which penetrate into the Earth's magnetosphere. SEPs with large enough energy induce a complicated atmospheric cascade, which secondary particles lead to an enhancement of count rate of ground-based detectors e.g. Neutron Monitors (NMs). This class of SEPs is therefore referred as Ground Level Enhancements (GLEs). The characterisation of the high-energy SEPs environment with corresponding space weather effects is important for space flights, aviation, and satellite industry. In this topical issue recent developments, addressing important user needs in the space radiation environment domain are published. Some articles are relevant to the specification of the SEP environment whilst others focus on space weather prediction of SEP fluxes. Catalogues based on measurement and processing of SEPs including ground-based data, and modelling of aircrew radiation exposure during major events are also presented.

Assessment of the Radiation Environment at Commercial Jet-Flight Altitudes During GLE 72 on 10 September 2017 Using Neutron Monitor Data

A. L. **Mishev** , I. G. Usoskin
Space Weather 16, 12 1921-1929 **2018**
sci-hub.tw/10.1029/2018SW001946
As a result of intense solar activity during the first 10 days of September, a ground level enhancement occurred on 10 September 2017. Here we computed the effective dose rates in the polar region at several altitudes during the event using the derived rigidity spectra of the energetic solar protons. The contribution of different populations of energetic particles, namely, galactic cosmic rays and solar protons, to the exposure is explicitly considered and compared. We also assessed the exposure of a crew members/passengers to radiation at different locations and at several cruise flight altitudes and calculated the received doses for two typical intercontinental flights. The estimated received dose during a high latitude, 40 kft, ∼10-hr flight is ∼100 μSv.
See Eos Buzz Newsletter: 26 April **2019**

Neutron monitor count rate increase as a proxy for dose rate assessment at aviation altitudes during GLEs

Alexander **Mishev**1,2*, Sasu Tuohino3 and Ilya Usoskin
J. Space Weather Space Clim. **2018**, 8, A46
https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc170098.pdf
Radiation exposure due to cosmic rays, specifically at cruising aviation altitudes, is an important topic in the field of space weather. While the effect of galactic cosmic rays can be easily assessed on the basis of recent models, estimate of the dose rate during strong solar particle events is rather complicated and time consuming. Here we compute the maximum effective dose rates at a typical commercial flight altitude of 35 kft (11 000 m above sea level) during ground level enhancement events, where the necessary information, namely derived energy/rigidity spectra of solar energetic particles, is available. The computations are carried out using different reconstructions of the solar proton spectra, available in bibliographic sources, leading to multiple results for some events. The computations were performed employing a recent model for effective dose and/or ambient dose equivalent due to cosmic ray particles. A conservative approach for the computation was assumed. A highly significant correlation between the maximum effective dose rate and peak NM count rate increase during ground level enhancement events is derived. Hence, we propose to use the peak NM count rate increase as a proxy in order to assess the peak effective dose rate at flight altitude during strong solar particle events using the real time records of the worldwide global neutron monitor network.
Table 2. Assessed maximum effective dose rates at the altitude of 35 kft a.s.l. in a region with Pc < 1 GV during GLE events. (1956-2017)

Assessment of spectral and angular characteristics of sub-GLE events using the global neutron monitor network

Alexander **Mishev**1*, Stepan Poluianov1,2 and Ilya Usoskin1,2
J. Space Weather Space Clim. **2017**, 7, A28
https://www.swsc-journal.org/articles/swsc/pdf/2017/01/swsc170026.pdf
New recently installed high-altitude polar neutron monitors (NMs) have made the worldwide NM network more sensitive to strong solar energetic particle (SEP) events, registered at ground level, namely ground-level enhancement (GLE) events. The DOMC/B and South Pole NMs in addition to marginal cut-off rigidity also possess lower atmospheric cut-off compared to the sea level. As a result, the two high-altitude polar NM stations are able to detect lower energy SEP events, which most likely would not be registered by the other (near sea level) NMs. Here, we consider several candidates for such type of events called sub-GLEs. Using the worldwide NM database (NMDB) records and an optimization procedure combined with simulation of the global NM network response, we assess the spectral and angular characteristics of sub-GLE particles. With the estimated spectral characteristics as an

input, we evaluate the effective dose rate in polar and sub-polar regions at typical commercial flight altitude. Hence, we demonstrate that the global NM network is a useful tool to estimate important space weather effects, e.g., the aircrew exposure due to cosmic rays of galactic and/or solar origins. **07/03/2012, 06/01/2014, 29/10/2015**

Computation of dose rate at flight altitudes during ground level enhancements no. 69, 70 and 71

A.L. **Mishev**, F. Adibpourb, I.G. Usoskinc, d, E. Felsbergerb

Advances in Space Research, Volume 55, Issue 1, 1 January **2015**, Pages 354–362

http://www.sciencedirect.com/science/article/pii/S0273117714003822

A new numerical model of estimating and monitoring the exposure of personnel due to secondary cosmic radiation onboard aircraft, in accordance with radiation safety standards as well as European and national regulations, has been developed. The model aims to calculate the effective dose at flight altitude (39,000 ft) due to secondary cosmic radiation of galactic and solar origin. In addition, the model allows the estimation of ambient dose equivalent at typical commercial airline altitudes in order to provide comparison with reference data. The basics, structure and function of the model are described. The model is based on a straightforward full Monte Carlo simulation of the cosmic ray induced atmospheric cascade. The cascade simulation is performed with the PLANETOCOSMICS code. The flux of secondary particles, namely neutrons, protons, gammas, electrons, positrons, muons and charged pions is calculated. A subsequent conversion of the particle fluence into the effective dose or ambient dose equivalent is performed as well as a comparison with reference data. An application of the model is demonstrated, using a computation of the effective dose rate at flight altitude during the ground level enhancements of **20 January 2005, 13 December 2006 and 17 May 2012.**

THE ORIGIN OF SEP EVENTS: NEW RESEARCH COLLABORATION AND NETWORK ON SPACE WEATHER

Rositsa **Miteva**1, Larisa Kashapova2, Irina Myagkova3, Nataliia Meshalkina2, Nikola Petrov4, Andrey Bogomolov3, Ivan Myshyakov2, Tsvetan Tsvetkov4, Dimitar Danov1, Dmitriy Zhdanov

https://www.researchgate.net/publication/321292236_THE_ORIGIN_OF_SEP_EVENTS_NEW_RESEARCH_COLLABORATION_AND_NETWORK_ON_SPACE_WEATHER?discoverMore=1

2017

A new project on the solar energetic particles (SEPs) and their solar origins (flares and coronal mass ejections) is described here. The main aim of this project is to answer the question – whether the SEPs observed in situ are driven by flares, by CMEs or both accelerators contribute to an extent which varies from event to event – by deducing a quantitative measure of the flare vs. CME contribution, duration and efficiency. New observations (SONG/Koronas-F, Relec/Vernov) and new approaches of analysis will be utilized (e.g., magnetic topology of active regions using 3D extrapolation techniques of detailed case studies together with statistical analysis of the phenomena). In addition, the identification of the uncertainty limits of SEP injection, onset time and testing the validity of assumptions often taken for granted (association procedures, solar activity longitudinal effects, correlation analysis, etc.) are planned. The project outcomes have the capacity to contribute to other research fields for improvement of modeling schemes and forecasting methods of space weather events.

Operational models and drag-derived density trends in the thermosphere

Moe, Kenneth; Moe, Mildred M.

Space Weather, Vol. 9, No. 0, S00E10, **2011**

http://dx.doi.org/10.1029/2010SW000650

Improvements in knowledge of satellite drag coefficients confirm current reports of a long-term decline in thermospheric density. Operational thermospheric models, though highly sophisticated, did not predict the extent of the decline, posing a problem for orbit control and maintenance. Evidence is presented that current models could not predict the magnitude of the decline for two reasons: (1) they do not realistically describe the highly variable energy entering the thermosphere from the solar wind at all times, especially at geomagnetically quiet times, and (2) they overestimate the less volatile ultraviolet contribution by ignoring eddy diffusion which transfers energy from the thermosphere to the mesosphere. The historical background of operational thermospheric models and suggestions for improvement are provided.

Credit where credit is due: Data and software in the space weather community

S. K. **Morley**, H. Liu, B. A. Carter, J. L. Gannon, N. Lugaz

Space Weather e2022SW003371 **Volume20, Issue12** **2022**

https://doi.org/10.1029/2022SW003371

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022SW003371

This editorial aims to improve awareness of the current best practices in open research, and stimulate discussion on the practical implementation of AGU's data and software policy in key areas of space weather research. We also further aim to encourage authors to take additional steps to ensure clear credit to all contributors to the work, whether that is underlying data, key software, or direct contributions to the manuscript.

Challenges and opportunities in magnetospheric space weather prediction **Review**

S.K. **Morley**

Space Weather **2020**

https://doi.org/10.1029/2018SW002108

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2018SW002108

Space Weather is the study of the dynamics of the coupled Solar-Terrestrial environment, as these dynamics impact technological systems and human activity. This paper reviews a selection of the advances, challenges, and new opportunities for magnetospheric space weather, and while the focus is on specific phenomena, many other aspects of space weather will have similar challenges and needs. As a scientific field with direct applications, the field of space weather is partly driven by imperatives from both policy and operations. We provide an introduction to some of the context in which the field exists, and discuss how this might shape future developments and norms within the space weather enterprise. We briefly examine benchmarking, as a policy- and operationally-driven activity, as it provides immediate societal relevance and an opportunity to stretch scientific understanding. As numerical space weather prediction now becomes routine, and exascale computing is in the near-future, we identify challenges relating to computational expense and big data, capturing and accounting for uncertainties, and specification of boundary conditions. Here, as with the observations supporting numerical space weather prediction, the key challenge lies in extending the lead time of predictions. We also discuss the role of data, particularly in regard to model validation and empirical modeling. Due to the growing societal impact of space weather we also examine the relationships between space weather and its terrestrial counterpart, and look at the importance of continuous evaluation, monitoring progress in predictive capability, and communication with researchers, forecasters, and end users.

The Global Positioning System constellation as a space weather monitor: Comparison of electron measurements with Van Allen Probes data

Steven K. **Morley**, John P. Sullivan, Michael G. Henderson, J. Bernard Blake, Daniel N. Baker

Space Weather Volume 14, Issue 2 February **2016** Pages 76–92

http://onlinelibrary.wiley.com/doi/10.1002/2015SW001339/full

https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015SW001339

This paper establishes the scientific utility of the Combined X-ray Dosimeter (CXD), currently flown on 19 satellites in the Global Positioning System (GPS) constellation, by cross-calibrating energetic electron measurements against data from the Van Allen Probes. By breaking our cross calibration into two parts—one that removes any spectral assumptions from the CXD flux calculation and one that compares the energy spectra—we first validate the modeled instrument response functions, then the calculated electron fluxes. Unlike previous forward modeling of energetic electron spectra, we use a combination of four distributions that together capture a wide range of observed spectral shapes. Our two-step approach allowed us to identify, and correct for, small systematic offsets between block IIR and IIF satellites. Using the Magnetic Electron Ion Spectrometer and Relativistic Electron-Proton Telescope on Van Allen Probes as a "gold standard," we demonstrate that the CXD instruments are well understood. A robust statistical analysis shows that CXD and Van Allen Probes fluxes are similar and the measured fluxes from CXD are typically within a factor of 2 of Van Allen Probes at energies 4 MeV. We present data from 17 CXD-equipped GPS satellites covering the 2015 "St. Patrick's Day" geomagnetic storm to illustrate the scientific applications of such a high data density satellite constellation and therefore demonstrate that the GPS constellation is positioned to enable new insights in inner magnetospheric physics and space weather forecasting.

Solar Flares: Origin and Threat to our Civilization

Nils-Axel **Mörner**

a new monograph " **SOLAR FLARES: Investigations and selected Research**" , Chapter 1 P. 1-11

2016

See **File** Chernov_News on Zebra Patterns_ Flare Book.pdf

http://www.nova-authors.com/___Encrypted/WEB_Links_Storage/e-Books/978-1-53610-221-5_eBook.pdf

Exploring Coronal Dynamics: A Next Generation Solar Physics Mission white paper

R. J. **Morton**, E. Scullion, D. S. Bloomfield, J. A. McLaughlin, S. Regnier, S. W. McIntosh, S. Tomczyk, P. Young

2016

https://arxiv.org/pdf/1611.06149v1.pdf

Determining the mechanisms responsible for the heating of the coronal plasma and maintaining and accelerating the solar wind are long standing goals in solar physics. There is a clear need to constrain the energy, mass and momentum flux through the solar corona and advance our knowledge of the physical process contributing to these fluxes. Furthermore, the accurate forecasting of Space Weather conditions at the near-Earth environment and, more generally, the plasma conditions of the solar wind throughout the heliosphere, require detailed knowledge of these fluxes in the near-Sun corona. Here we present a short case for a space-based imaging-spectrometer coronagraph, which will have the ability to provide synoptic information on the coronal environment and provide strict constraints on the mass, energy, and momentum flux through the corona. The instrument would ideally achieve cadences of ~10~s, spatial resolution of 1" and observe the corona out to 2~$R_{\sun}$. Such an

instrument will enable significant progress in our understanding of MHD waves throughout complex plasmas, as well as potentially providing routine data products to aid Space Weather forecasting.

On the effect of geomagnetic storms on relativistic electrons in the outer radiation belt: Van Allen Probes observations†

Pablo. S. **Moya**, Víctor A. Pinto, David G. Sibeck, Shrikanth G. Kanekal, Daniel N. Baker

JGR **2017**

http://sci-hub.cc/http://onlinelibrary.wiley.com/doi/10.1002/2017JA024735/abstract;jsessionid=48E043E86C22084A1908FD5A8ADEDAFC.f03t01

Using Van Allen Probes ECT-REPT observations we performed a statistical study on the effect of geomagnetic storms on relativistic electrons fluxes in the outer radiation belt for 78 storms between September 2012 and June 2016. We found that the probability of enhancement, depletion and no change in flux values depends strongly on L and energy. Enhancement events are more common for ∼ 2 MeV electrons at L ∼ 5, and the number of enhancement events decreases with increasing energy at any given L shell. However, considering the percentage of occurrence of each kind of event, enhancements are more probable at higher energies, and the probability of enhancement tends to increases with increasing L shell. Depletion are more probable for 4-5 MeV electrons at the heart of the outer radiation belt, and no change events are more frequent at L < 3.5 for E~ 3 MeV particles. Moreover, for L > 4.5 the probability of enhancement, depletion or no-change response presents little variation for all energies. Because these probabilities remain relatively constant as a function of radial distance in the outer radiation belt, measurements obtained at Geosynchronous orbit may be used as a proxy to monitor E≥1.8 MeV electrons in the outer belt. **14 Nov 2012 1 June 2013, 8 May 2016**

SOLAR CYCLE PROPAGATION, MEMORY, AND PREDICTION: INSIGHTS FROM A CENTURY OF MAGNETIC PROXIES

Andrés **Muñoz-Jaramillo**1,2,3, María Dasi-Espuig4, Laura A. Balmaceda5, and Edward E. DeLuca

2013 ApJ 767 L25

The solar cycle and its associated magnetic activity are the main drivers behind changes in the interplanetary environment and Earth's upper atmosphere (commonly referred to as space weather). These changes have a direct impact on the lifetime of space-based assets and can create hazards to astronauts in space. In recent years there has been an effort to develop accurate solar cycle predictions (with aims at predicting the long-term evolution of space weather), leading to nearly a hundred widely spread predictions for the amplitude of solar cycle 24. A major contributor to the disagreement is the lack of direct long-term databases covering different components of the solar magnetic field (toroidal versus poloidal). Here, we use sunspot area and polar faculae measurements spanning a full century (as our toroidal and poloidal field proxies) to study solar cycle propagation, memory, and prediction. Our results substantiate predictions based on the polar magnetic fields, whereas we find sunspot area to be uncorrelated with cycle amplitude unless multiplied by area-weighted average tilt. This suggests that the joint assimilation of tilt and sunspot area is a better choice (with aims to cycle prediction) than sunspot area alone, and adds to the evidence in favor of active region emergence and decay as the main mechanism of poloidal field generation (i.e., the Babcock-Leighton mechanism). Finally, by looking at the correlation between our poloidal and toroidal proxies across multiple cycles, we find solar cycle memory to be limited to only one cycle.

The Importance of Ensemble Techniques for Operational Space Weather Forecasting

Sophie A. **Murray**

Space Weather Volume16, Issue7 July 2018 Pages 777-783

https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2018SW001861

The space weather community has begun to use frontier methods such as data assimilation, machine learning, and ensemble modeling to advance current operational forecasting efforts. This was highlighted by a multidisciplinary session at the 2017 American Geophysical Union Meeting, Frontier Solar-Terrestrial Science Enabled by the

Combination of Data-Driven Techniques and Physics-Based Understanding, with considerable discussion surrounding ensemble techniques. Here ensemble methods are described in detail, using a set of predictions to improve on a single-model output, for example, taking a simple average of multiple models, or using more complex techniques for data assimilation. They have been used extensively in fields such as numerical weather prediction and data science, for both improving model accuracy and providing a measure of model uncertainty. Researchers in the space weather community have found them to be similarly useful, and some examples of success stories are highlighted in this commentary. Future developments are also encouraged to transition these basic research efforts to operational forecasting as well as providing prediction errors to aid end-user understanding.

Flare forecasting at the Met Office Space Weather Operations Centre

Sophie A. **Murray**, Suzy Bingham, Michael Sharpe, David R. Jackson
SpaceWeather **2017**
https://arxiv.org/pdf/1703.06754.pdf

The Met Office Space Weather Operations Centre produces 24/7/365 space weather guidance, alerts, and forecasts to a wide range of government and commercial end users across the United Kingdom. Solar flare forecasts are one of its products, which are issued multiple times a day in two forms; forecasts for each active region on the solar disk over the next 24 hours, and full-disk forecasts for the next four days. Here the forecasting process is described in detail, as well as first verification of archived forecasts using methods commonly used in operational weather prediction. Real-time verification available for operational flare forecasting use is also described. The influence of human forecasters is highlighted, with human-edited forecasts outperforming original model results, and forecasting skill decreasing over longer forecast lead times.

Space Weather Forecasting and Research at the Met Office

Sophie **Murray**
UKSP Nugget #58, May **2015**
http://www.uksolphys.org/uksp-nugget/58-space-weather-forecasting-and-research-at-the-met-office/
Met Office Space Weather Operations Centre (MOSWOC)

MOSWOC forecasters provide space weather alerts, warnings, and guidance documents related to current solar and geomagnetic activity. This service provides timely advice of the impacts of space weather on UK services and infrastructure to Government and responder communities.

Proxy Index Derived From All Sky Imagers for Space Weather Impact on GPS

Sajan C. **Mushini**, Susan Skone, Emma Spanswick, Eric Donovan, Maryam Najmafshar
Space Weather Volume16, Issue7 July **2018** Pages 838-848
http://sci-hub.se/10.1029/2018SW001919

Global Positioning System (GPS) signals passing through the auroral ionosphere, which exhibits multiscreen electron density structuring, maybe scintillated causing observation and possibly positioning errors. It is advantageous to determine the magnitude of GPS signal scintillation associated with a given level of auroral brightness observed around the signal's ionospheric pierce point (IPP). Such information would enable the exploitation of auroral image observations in space weather monitoring and help in assessment of impact on infrastructure/services reliant on GNSS. Studies have observed a general positive correlation between auroral brightness and GPS phase scintillation but not a definite one-to-one relationship. In this study a correlation coefficient of 0.38 is observed between the phase scintillation and the level of auroral arc brightness around the GPS signal's raypath for a data set of 292 events in the Canadian sector. Alternatively, a new pseudo-scintillation index, Rate of change of Brightness index, is introduced in this study which is derived from the changing auroral brightness around the satellite's IPP. This Rate of change of Brightness index is highly positively correlated (correlation coefficient: 0.75) with GPS phase scintillation. Spatial and spectral relationships between auroral brightness around the satellite's IPP and phase scintillation were also analyzed. It is observed that probability of GPS signals experiencing phase scintillation is high when the auroral brightness around the satellite's IPP has dominant fluctuations in the frequency band ~0.06 to 0.16 Hz. These results indicate that GPS signal scintillation is related to the dynamics of the brightness around the satellite's IPP as the satellite signal propagates through the aurora.

Physics-based Approach to Thermospheric Density Estimation using CubeSat GPS Data

Shaylah M. **Mutschler**, Penina Axelrad, Eric K. Sutton, Dallas Masters
Space Weather e2021SW002997 **Volume21, Issue1** **2023**
agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021SW002997

In Low Earth Orbit (LEO), atmospheric drag is the largest contributor to trajectory prediction error. The current thermospheric density model used in operations, the High Accuracy Satellite Drag Model (HASDM), applies corrections to an empirical density model every 3 hours using observations of 75+ calibration satellites. This work aims to improve global thermospheric density estimation by utilizing a physics-based space environment model and precise GPS-based orbit estimates of LEO CubeSats. The data assimilation approach presented here estimates drivers of the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM) every 1.5 hours using CubeSat GPS information. In this work, Spire Global CubeSat data are used to demonstrate the method using only ten satellites; the true strength of the method is its potential to exploit data already collected on large LEO constellations (hundreds of CubeSats). Precise Orbit Determination (POD) information from ten CubeSats over 12 days is used to sense a global density field when Kp historical data show a minor and moderate geomagnetic storm in succession. This paper provides a direct comparison of estimated density, derived by our new method, to HASDM and Swarm mission derived density. A propagation analysis is also executed by comparing the CubeSat POD data to orbits propagated using our estimated density versus HASDM density. The analyses show that the estimated density is within 35% of HASDM during storm-time conditions, and that the propagation using the estimated density yields an improvement of 26% over NRLMSISE-00 compared to HASDM, while outperforming HASDM during the second storm peak.

Time Domain Simulation of Geomagnetically Induced Current (GIC) Flowing in 500-kV Power Grid in Japan Including a Three-Dimensional Ground Inhomogeneity

S. **Nakamura** Y. Ebihara S. Fujita T. Goto N. Yamada S. Watari Y. Omura

Space Weather 16?, 12, Pages: 1946-1959, **2018** 10.1029/2018SW002004

We performed 3-D time domain simulation of geomagnetically induced currents (GICs) flowing in the Japanese 500-kV power grid. The three-dimensional distribution of the geomagnetically induced electric field (GIE) was calculated by using the finite difference time domain method with a three-dimensional electrical conductivity model constructed from a global relief model and a global map of sediment thickness. First, we imposed a uniform sheet current at 100-km altitude with a sinusoidal perturbation to illuminate the influence of the structured ground conductivity on GIE and GIC. The simulation result shows that GIE exhibits localized, uneven distribution that can be attributed to charge accumulation due to the inhomogeneous conductivity below the Earth's surface. The charge accumulation becomes large when the conductivity gradient vector is parallel or antiparallel to the incident electric field. For given GIE, we calculated the GICs flowing in a simplified 500-kV power grid network in Japan. The influence of the inhomogeneous ground conductivity on GIC appears to depend on a combination of the location of substations and the direction of the source current. Uneven distribution of the power grid system gives rise to intensification of the GICs flowing in remote areas where substations/power plants are distributed sparsely. Second, we imposed the sheet current with its intensity inferred from the ground magnetic disturbance for the magnetic storm of 27 May 2017. We compared the calculated GICs with the observed ones at substations around Tokyo and found a certain agreement when the uneven distribution of GIE is incorporated with the simulation.

Twisted solar active region magnetic fields as drivers of space weather: Observational and theoretical investigations

Dibyendu **Nandy**, Duncan H. Mackay, Richard C. Canfield and P.C.H. Martens

Journal of Atmospheric and Solar-Terrestrial Physics
Volume 70, Issues 2-4, February **2008**, Pages 605-613

The properties and dynamics of magnetic fields on the Sun's photosphere and outer layers—notably those within solar active regions—govern the eruptive activity of the Sun. These photospheric magnetic fields also act as the evolving lower boundary of the Sun–Earth coupled system. Quantifying the physical attributes of these magnetic fields and exploring the mechanisms underlying their influence on the near-Earth space environment are of vital importance for forecasting and mitigating adverse space weather effects. In this context, we discuss here a novel technique for measuring twist in the magnetic field lines of solar active regions that does not invoke the force-free field assumption. Twist in solar active regions can play an important role in flaring activity and the initiation of CMEs via the kink instability mechanism; we outline a procedure for determining this solar active region eruptive potential. We also discuss how twist in active region magnetic fields can be used as inputs in simulations of the coronal and heliospheric fields; specifically, we explore through simulations, the formation, evolution and ejection of magnetic flux ropes that originate in twisted magnetic structures. The results and ideas presented here are relevant for exploring the role of twisted solar active region magnetic fields and flux ropes as drivers of space weather in the Sun–Earth system.

Importance of predicting the dose temporal profile for large solar energetic particle events

Neal, John S.; Nichols, Theodore F.; Townsend, Lawrence W.
Space Weather, Vol. 6, No. 9, S09004
http://dx.doi.org/10.1029/2008SW000393

Scientists argue that predicting the arrival time and intensity of the shock from a coronal mass ejection is not enough to prevent astronauts from exposure to harmful radiation; instead, forecasters must predict the changes in dose at a given location over several days following any given event.

Automatic detection of Interplanetary Coronal Mass Ejections from in-situ data: a deep learning approach

Gautier **Nguyen**, Nicolas Aunai, Dominique Fontaine, Erwan Le Pennec, Joris Van den Bossche, Alexis Jeandet, Brice Bakkali, Louis Vignoli, Bruno Regaldo-Saint Blancar

2019

https://arxiv.org/pdf/1903.10780.pdf

Decades of studies have suggested several criteria to detect Interplanetary coronal mass ejections (ICME) in time series from in-situ spacecraft measurements. Among them the most common are an enhanced and smoothly rotating magnetic field, a low proton temperature and a low plasma beta. However, these features are not all observed for each ICME due to their strong variability. Visual detection is time-consuming and biased by the observer interpretation leading to non exhaustive, subjective and thus hardly reproducible catalogs. Using convolutional neural networks on sliding windows and peak detection, we provide a fast, automatic and multi-scale detection of ICMEs. The method has been tested on the in-situ data from WIND between 1997 and 2015 and on the 657 ICMEs that were recorded during this period. The method offers an unambiguous visual proxy of ICMEs that gives an interpretation of the data similar to what an expert observer would give. We found at a maximum 197 of the 232 ICMEs of the 2010-2015 period (recall 84 +-4.5 % including 90% of the ICMEs present in the lists of Nieves-Chinchilla et al. (2015) and Chi et al. (2016). The minimal number of False Positives was 25 out of 158 predicted ICMEs (precision 84+-2.6%). Although less accurate, the method also works with one or several missing input parameters. The method has the advantage of improving its performance by just increasing the amount of input data. The generality of the method paves the way for automatic detection of many different event signatures in spacecraft in-situ measurements. **2011-03-30, 3 July 2012, 17 July 2012.**

Chapter 8 - An Overview of Science Challenges Pertaining to Our Understanding of Extreme Geomagnetically Induced Currents

Chigomezyo M.**Ngwira***†Antti A.Pulkkinen†

In: Extreme Events in Geospace Origins, Predictability, and Consequences **2018**, Pages 187-208
http://sci-hub.tw/10.1016/B978-0-12-812700-1.00008-X

Vulnerability of man-made infrastructure to Earth-directed space weather events is a serious concern for today's technology-dependent society. Space weather-driven geomagnetically induced currents (GICs) can disrupt the operation of extended electrically conducting technological systems. The threat of adverse impacts on critical technological infrastructure, such as power grids, oil and gas pipelines, and communication networks, has sparked renewed interest in extreme space weather. Because extreme space weather events have a low occurrence rate but a potentially high impact, this presents a major challenge for our understanding of extreme GIC activity. In this chapter, we discuss some of the key science challenges pertaining to our understanding of extreme events. In addition, we present an overview of GICs, including highlights of severe impacts over the last 80 years and recent U.S. federal actions relevant to this community. **May 15, 2005 , March 17, 2015 , October 7, 2015,**

Modeling extreme "Carrington-type" space weather events using three-dimensional global MHD simulations

Chigomezyo M. **Ngwira** , Antti Pulkkinen , Maria M. Kuznetsova , Alex Glocer
JGR Volume119, Issue6 June **2014** Pages 4456-4474
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2013JA019661

There is a growing concern over possible severe societal consequences related to adverse space weather impacts on man-made technological infrastructure. In the last two decades, significant progress has been made toward the first-principles modeling of space weather events, and three-dimensional (3-D) global magnetohydrodynamics (MHD) models have been at the forefront of this transition, thereby playing a critical role in advancing our understanding of space weather. However, the modeling of extreme space weather events is still a major challenge even for the modern global MHD models. In this study, we introduce a specially adapted University of Michigan

3-D global MHD model for simulating extreme space weather events with a Dst footprint comparable to the Carrington superstorm of September 1859 based on the estimate by Tsurutani et. al. (2003). Results are presented for a simulation run with "very extreme" constructed/idealized solar wind boundary conditions driving the magnetosphere. In particular, we describe the reaction of the magnetosphere-ionosphere system and the associated induced geoelectric field on the ground to such extreme driving conditions. The model setup is further tested using input data for an observed space weather event of Halloween storm October 2003 to verify the MHD model consistence and to draw additional guidance for future work. This extreme space weather MHD model setup is designed specifically for practical application to the modeling of extreme geomagnetically induced electric fields, which can drive large currents in ground-based conductor systems such as power transmission grids. Therefore, our ultimate goal is to explore the level of geoelectric fields that can be induced from an assumed storm of the reported magnitude, i.e., Dst∼=−1600 nT.

Comment on "Modeling extreme "Carrington-type" space weather events using three-dimensional global MHD simulations" by C.M. Ngwira, A. Pulkkinen, M.M. Kuznetsova and A. Glocer"

Bruce T. **Tsurutani**, Gurbax S. Lakhina, Ezequiel Echer, Chinmaya Nayak, Anthony J. Mannucci, Xing Meng

JGR **Volume123, Issue2** Pages 1388-1392 **2018**

http://onlinelibrary.wiley.com/doi/10.1002/2017JA024779/epdf

Simulation of the 23 July 2012 extreme space weather event: What if this extremely rare CME was Earth directed?

Chigomezyo M. **Ngwira**, Antti Pulkkinen, M. Leila Mays, Maria M. Kuznetsova, A. B. Galvin, Kristin Simunac, Daniel N. Baker, Xinlin Li, Yihua Zheng and Alex Glocer

Space Weather, Volume 11, Issue 12, pages 671–679, December **2013**

http://onlinelibrary.wiley.com/doi/10.1002/2013SW000990/pdf

Extreme space weather events are known to cause adverse impacts on critical modern day technological infrastructure such as high-voltage electric power transmission grids. On 23 July 2012, NASA's Solar Terrestrial Relations Observatory-Ahead (STEREO-A) spacecraft observed in situ an extremely fast coronal mass ejection (CME) that traveled 0.96 astronomical units (∼1 AU) in about 19 h. Here we use the Space Weather Modeling Framework (SWMF) to perform a simulation of this rare CME. We consider STEREO-A in situ observations to represent the upstream L1 solar wind boundary conditions. The goal of this study is to examine what would have happened if this Rare-type CME was Earth-bound. Global SWMF-generated ground geomagnetic field perturbations are used to compute the simulated induced geoelectric field at specific ground-based active INTERMAGNET magnetometer sites. Simulation results show that while modeled global SYM-H index, a high-resolution equivalent of the Dst index, was comparable to previously observed severe geomagnetic storms such as the Halloween 2003 storm, the 23 July CME would have produced some of the largest geomagnetically induced electric fields, making it very geoeffective. These results have important practical applications for risk management of electrical power grids.

International Coordination and Support for SmallSat-enabled Space Weather Activities

Teresa **Nieves-Chinchilla**, Bhavya Lal, Robert Robinson, Amir Caspi, David R. Jackson, Therese Moretto Jørgensen, James Spann

Space Weather **Volume18, Issue12** e2020SW002568 **2020**

https://arxiv.org/ftp/arxiv/papers/2011/2011.04759.pdf

https://doi.org/10.1029/2020SW002568

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020SW002568

Advances in space weather science and small satellite (SmallSat) technology have proceeded in parallel over the past two decades, but better communication and coordination is needed among the respective worldwide communities contributing to this rapid progress. We identify six areas where improved international coordination is especially desirable, including: (1) orbital debris mitigation; (2) spectrum management; (3) export control regulations; (4) access to timely and low-cost launch opportunities; (5) inclusive data policies; and (6) education. We argue the need for internationally coordinated policies and programs to promote the use of SmallSats for space weather research and forecasting while realizing maximum scientific and technical advances through the integration of these two increasingly important endeavors.

Analysis of the Relationship Between the Solar X-Ray Radiation Intensity and the D-Region Electron Density Using Satellite and Ground-Based Radio Data

Aleksandra **Nina**, Vladimir M. Čadež, Jovan Bajčetić, Srdjan T. Mitrović…

Solar Physics April **2018**, 293:64

https://link.springer.com/content/pdf/10.1007%2Fs11207-018-1279-4.pdf

Increases in the X-ray radiation that is emitted during a solar X-ray flare induce significant changes in the ionospheric D region. Because of the numerous complex processes in the ionosphere and the characteristics of the radiation and plasma, the causal-consequential relationship between the X-ray radiation and ionospheric parameters is not easily determined. In addition, modeling the ionospheric D-region plasma parameters is very difficult because of the lack of data for numerous time- and space-dependent physical quantities. In this article we first give a qualitative analysis of the relationship between the electron density and the recorded solar X-ray intensity. After this, we analyze the differences in the relationships between the D-region response and various X-ray radiation properties. The quantitative study is performed for data observed on 5 May 2010 in the time period between 11:40 UT – 12:40 UT when the GOES 14 satellite detected a considerable X-ray intensity increase. Modeling the electron density is based on characteristics of the 23.4 kHz signal emitted in Germany and recorded by the receiver in Serbia.

Solar Flare Prediction Model with Three Machine-Learning Algorithms Using Ultraviolet Brightening and Vector Magnetogram

N. **Nishizuka**, K. Sugiura, Y. Kubo, M. Den, S. Watari, M. Ishii

2017 ApJ 835 156

https://arxiv.org/pdf/1611.01791v1.pdf

We developed a flare prediction model using machine learning, which is optimized to predict the maximum class of flares occurring in the following 24 h. Machine learning is used to devise algorithms that can learn from and make decisions on a huge amount of data. We used solar observation data during the period 2010-2015, such as vector magnetogram, ultraviolet (UV) emission, and soft X-ray emission taken by the Solar Dynamics Observatory and the Geostationary Operational Environmental Satellite. We detected active regions from the full-disk magnetogram, from which 60 features were extracted with their time differentials, including magnetic neutral lines, the current helicity, the UV brightening, and the flare history. After standardizing the feature database, we fully shuffled and randomly separated it into two for training and testing. To investigate which algorithm is best for flare prediction, we compared three machine learning algorithms: the support vector machine (SVM), k-nearest neighbors (k-NN), and extremely randomized trees (ERT). The prediction score, the true skill statistic (TSS), was higher than 0.9 with a fully shuffled dataset, which is higher than that for human forecasts. It was found that k-NN has the highest performance among the three algorithms. The ranking of the feature importance showed that the previous flare activity is most effective, followed by the length of magnetic neutral lines, the unsigned magnetic flux, the area of UV brightening, and the time differentials of features over 24 h, all of which are strongly correlated with the flux emergence dynamics in an active region. **2012 March 6**

Machine Learning in Heliophysics and Space Weather Forecasting: A White Paper of Findings and Recommendations

Gelu **Nita**, Manolis Georgoulis, Irina Kitiashvili, Viacheslav Sadykov, Enrico Camporeale, Alexander Kosovichev, et al.

Workshop Report **2020**

https://arxiv.org/pdf/2006.12224.pdf

The authors of this white paper met on 16-17 January 2020 at the New Jersey Institute of Technology, Newark, NJ, for a 2-day workshop that brought together a group of heliophysicists, data providers, expert modelers, and computer/data scientists. Their objective was to discuss critical developments and prospects of the application of machine and/or deep learning techniques for data analysis, modeling and forecasting in Heliophysics, and to shape a strategy for further developments in the field. The workshop combined a set of plenary sessions featuring invited introductory talks interleaved with a set of open discussion sessions. The outcome of the discussion is encapsulated in this white paper that also features a top-level list of recommendations agreed by participants.

Roadmap for Reliable Ensemble Forecasting of the Sun-Earth System

Gelu **Nita**, Rafal Angryk, Berkay Aydin, Juan Banda, Tim Bastian, Tom Berger, Veronica Bindi, Laura Boucheron, Wenda Cao, Eric Christian, Georgia de Nolfo, Edward DeLuca, Marc DeRosa, Cooper Downs, Gregory Fleishman, Olac Fuentes, Dale Gary, Frank Hill, Todd Hoeksema, Qiang Hu, Raluca Ilie,Jack Ireland, Farzad Kamalabadi, Kelly Korreck, Alexander Kosovichev, Jessica Lin, Noe Lugaz,Anthony Mannucci, Nagi Mansour, Petrus Martens, Leila Mays, James McAteer, Scott W. McIntosh,Vincent Oria, David Pan, Marco Panesi, Dean Pesnel, Alexei Pevtsov, Valentin Pillet, Laurel Rachmeler,Aaron Ridley, Ludger Scherliess, Gabor Toth, Marco Velli, Stephen White, Jie Zhang, Shasha Zou

Workshop Report **2018**

https://arxiv.org/pdf/1810.08728.pdf

The authors of this report met on 28-30 March 2018 at the New Jersey Institute of Technology, Newark, New Jersey, for a 3-day workshop that brought together a group of data providers, expert modelers, and computer and data scientists, in the solar discipline. Their objective was to identify challenges in the path towards building an effective framework to achieve transformative advances in the understanding and forecasting of the Sun-Earth system from the upper convection zone of the Sun to the Earth's magnetosphere. The workshop aimed to develop a research roadmap that targets the scientific challenge of coupling observations and modeling with emerging data-science research to extract knowledge from the large volumes of data (observed and simulated) while stimulating computer science with new research applications. The desire among the attendees was to promote future trans-disciplinary collaborations and identify areas of convergence across disciplines. The workshop combined a set of plenary sessions featuring invited introductory talks and workshop progress reports, interleaved with a set of breakout sessions focused on specific topics of interest. Each breakout group generated short documents, listing the challenges identified during their discussions in addition to possible ways of attacking them collectively. These documents were combined into this report-wherein a list of prioritized activities have been collated, shared and endorsed.

A comparative verification of forecasts from two operational solar wind models

Norquist, Donald C.; Meeks, Warner C.
Space Weather, Vol. 8, No. 12, S12005, **2010**
http://dx.doi.org/10.1029/2010SW000598

The solar wind (SW) and interplanetary magnetic field (IMF) have a significant influence on the near-Earth space environment. In this study we evaluate and compare forecasts from two models that predict SW and IMF conditions: the Hakamada-Akasofu-Fry (HAF) version 2, operational at the Air Force Weather Agency, and Wang-Sheeley-Arge (WSA) version 1.6, executed routinely at the Space Weather Prediction Center. SW speed (Vsw) and IMF polarity (Bpol) forecasts at L1 were compared with Wind and Advanced Composition Explorer satellite observations. Verification statistics were computed by study year and forecast day. Results revealed that both models' mean Vsw are slower than observed. The HAF slow bias increases with forecast duration. WSA had lower Vsw forecast-observation difference (F-O) absolute means and standard deviations than HAF. HAF and WSA Vsw forecast standard deviations were less than observed. Vsw F-O mean square skill rarely exceeds that of recurrence forecasts. Bpol is correctly predicted 65%–85% of the time in both models. Recurrence beats the models in Bpol skill in nearly every year forecast day category. Verification by “event” (flare events ≤5 days before forecast start) and “nonevent” (no flares) forecasts showed that most HAF Vsw bias growth, F-O standard deviation decrease, and forecast standard deviation decrease were due to the event forecasts. Analysis of single time step Vsw increases of ≥20% in the nonevent forecasts indicated that both models predicted too many occurrences and missed many observed incidences. Neither model had skill above a random guess in predicting Vsw increase arrival time at L1.

Predicting well-connected SEP events from observations of solar soft X-rays and near-relativistic electrons

Marlon **Núñez**
J. Space Weather Space Clim. **2018**, 8, A36
https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc180006.pdf

This paper studies the use of electron data from the Electron Proton Alpha Monitor (EPAM) on board the Advanced Composition Explorer (ACE) in the UMASEP (University of Málaga Solar particle Event Predictor) scheme [Núñez, Space Weather 9 (2011) S07003; Núñez, Space Weather 13 (2015)] for predicting well-connected >10 MeV Solar Energetic Proton (SEP) events. In this study, the identification of magnetic connection to a solar particle source is done by correlating Geostationary Operational Environmental Satellites (GOES) Soft X-Ray (SXR) fluxes with ACE EPAM electrons fluxes with energies of 0.175–0.375 MeV. The forecasting performance of this model, called Well-Connected Prediction with electrons (WCP-electrons), was evaluated for a 16-year period from November 2001 to October 2017. This performance is compared with that of the component of current real-time tool UMASEP-10, called here WCP-protons model, which predicts the same type of events by correlating GOES SXR with differential proton fluxes with energies of 9–500 MeV. For the aforementioned period, the WCP-electrons model obtained a Probability of Detection (POD) of 50.0%, a False Alarm Ratio (FAR) of 39% and an Average Warning Time (AWT) of 1 h 44 min. The WCP-protons model obtained a POD of 78.0%, a FAR of 22% and an AWT of 1 h 3 min. These results show that the use of ACE EPAM electron data in the UMASEP scheme obtained a better anticipation time (additional 41 min on average) but a lower performance in terms of POD and FAR. We also analyzed the use of a combined model, composed of WCP-electrons and WCP-protons, working in parallel (i.e. the combined model issues a forecast when any of the individual models emits a forecast). The combined model obtained the best POD (84%), and a FAR and AWT (34.4% and 1 h 34 min, respectively) which is in between those of the individual models. **April 11, 2013**

Table 1. Forecasting results of the WCP-electrons and WCP-protons model for predicting all prompt SEP events with energies >10 MeV which occurred from November 2001 to October 2017

Real-time prediction of the occurrence of GLE events

Marlon **Núñez**, Pedro J. Reyes-Santiago, Olga E. Malandraki
Space Weather Volume 15, Issue 7 July **2017** Pages 861–873
http://sci-hub.cc/10.1002/2017SW001605
A tool for predicting the occurrence of Ground Level Enhancement (GLE) events using the UMASEP scheme is presented. This real-time tool, called HESPERIA UMASEP-500, is based on the detection of the magnetic connection, along which protons arrive in the near-Earth environment, by estimating the lag correlation between the time derivatives of 1 min soft X-ray flux (SXR) and 1 min near-Earth proton fluxes observed by the GOES satellites. Unlike current GLE warning systems, this tool can predict GLE events before the detection by any neutron monitor (NM) station. The prediction performance measured for the period from 1986 to 2016 is presented for two consecutive periods, because of their notable difference in performance. For the 2000–2016 period, this prediction tool obtained a probability of detection (POD) of 53.8% (7 of 13 GLE events), a false alarm ratio (FAR) of 30.0%, and average warning times (AWT) of 8 min with respect to the first NM station's alert and 15 min to the GLE Alert Plus's warning. We have tested the model by replacing the GOES proton data with SOHO/EPHIN proton data, and the results are similar in terms of POD, FAR, and AWT for the same period. The paper also presents a comparison with a GLE warning system. **28 October 2003**,
Table 1. Forecasting results for GLE events from 1986 to 2016

Prediction of shock arrival times from CME and flare data

Marlon **Núñez**, Teresa Nieves-Chinchilla, Antti Pulkkinen
Space Weather Volume 14, Issue 8 August **2016** Pages 544–562
https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2016SW001361
This paper presents the Shock Arrival Model (SARM) for predicting shock arrival times for distances from 0.72 AU to 8.7 AU by using coronal mass ejections (CME) and flare data. SARM is an aerodynamic drag model described by a differential equation that has been calibrated with a data set of 120 shocks observed from 1997 to 2010 by minimizing the mean absolute error (MAE), normalized to 1 AU. SARM should be used with CME data (radial, earthward, or plane-of-sky speeds) and flare data (peak flux, duration, and location). In the case of 1 AU, the MAE and the median of absolute errors were 7.0 h and 5.0 h, respectively, using the available CME/flare data. The best results for 1 AU (an MAE of 5.8 h) were obtained using both CME data, either radial or cone model-estimated speeds, and flare data. For the prediction of shock arrivals at distances from 0.72 AU to 8.7 AU, the normalized MAE and the median were 7.1 h and 5.1 h, respectively, using the available CME/flare data. SARM was also calibrated to be used with CME data alone or flare data alone, obtaining normalized MAE errors of 8.9 h and 8.6 h, respectively, for all shock events. The model verification was carried out with an additional data set of 20 shocks observed from 2010 to 2012 with radial CME speeds to compare SARM with the empirical ESA model and the numerical MHD-based ENLIL model. The results show that the ENLIL's MAE was lower than the SARM's MAE, which was lower than the ESA's MAE. The SARM's best results were obtained when both flare and true CME speeds were used.

Response of the Ionosphere-Plasmasphere Coupling to the September 2017 Storm: What Erodes the Plasmasphere so Severely?

Yuki **Obana**, Naomi Maruyama, Atsuki Shinbori, Kumiko K. Hashimoto, Mariangel Fedrizzi et al.
Space Weather Volume17, Issue6 Pages 861-876 **2019**
sci-hub.se/10.1029/2019SW002168
We report an extreme erosion of the plasmasphere arising from the September 2017 storm. The cold electron density is identified from the upper limit frequency of upper hybrid resonance waves observed by the Plasma Wave Experiment (PWE) instrument onboard the Exploration of energization and Radiation in Geospace (ERG)/Arase satellite. The electron density profiles reveal that the plasmasphere was severely eroded during the recovery phase of the storm and the plasmapause was located at L=1.6~1.7 at 23 UT **8 Sep 2017**. This is the first report of deep erosion of the plasmasphere (LPP<2) with the in-situ observation of the electron density. The degree of the severity is much more than what is expected from the relatively moderate value of the SYM-H minimum (–146 nT). We attempt to find a possible explanation for the observed severe depletion by using both observational evidence and numerical simulations. Our results suggest that the middle latitude electric field had penetrated from the high-latitude storm time convection for several hours. Such an unusually long-lasting penetration event can cause this observed degree of severity.

Space Weather impact on the degradation of NOAA POES MEPED proton detectors

Linn-Kristine Glesnes **Ødegaard***, Hilde Nesse Tyssøy, Marit Irene Jakobsen Sandanger, Johan Stadsnes and Finn Søraas
J. Space Weather Space Clim., 6, A26 (**2016**)
http://www.swsc-journal.org/articles/swsc/pdf/2016/01/swsc150080.pdf
The Medium Energy Proton and Electron Detector (MEPED) on board the National Oceanic and Atmospheric Administration Polar Orbiting Environmental Satellites (NOAA POES) is known to degrade with time. In recent years a lot of effort has been put into calibrating the degraded proton detectors. We make use of previous work and show that the degradation of the detectors can be attributed to the radiation dose of each individual instrument. However, the effectiveness of the radiation in degrading the detector is modulated when it is weighted by the mean ap index, increasing the degradation rate in periods with high geomagnetic activity, and decreasing it through periods of low activity. When taking ap and the radiation dose into account, we find that the degradation rate is independent of spacecraft and detector pointing direction. We have developed a model to estimate the correction factor for all the MEPED detectors as a function of accumulated corrected flux and the ap index. We apply the routine to NOAA POES spacecraft starting with NOAA-15, including the European satellites MetOp-02 and MetOp-01, and estimate correction factors.

Space Weather – Impacts, Mitigation and Forecasting **Review**
Sten **Odenwald**
http://www.spaceweather.org/ISES/swxeff/5.pdf
See "mitigation of impacts of space weather storms":
http://www.metoffice.gov.uk/publicsector/emergencies/space-weather/impacts
http://www.raeng.org.uk/publications/reports/space-weather-full-report
https://www.lloyds.com/~/media/lloyds/reports/360/360%20space%20weather/7311_lloyds_360_space%20weather_03.pdf
http://www.earthmagazine.org/article/dangers-solar-storms-which-gives-power-can-also-take-it-away

Spatio-temporal influence of solar activity on global air temperature
S. T. **Ogunjo**, A. B. Rabiu
Sun and Geosphere **2023**
https://arxiv.org/pdf/2305.17988
Previous studies on the impact and influence of solar activity on terrestrial weather has yielded contradictory results in literature. Present study presents, on a global scale, the correlation between surface air temperature and two solar activity indices (Sunspot number, 'Rz', and solar radio flux at 10.7, 'F10.7') at different time scales during solar cycle 23. Global air temperature has higher correlation values of ±0.8 with F10.7 compared to Rz (±0.3). Our results showed hemispheric delineation of the correlation between air temperature and solar activity with negative correlation in the southern hemisphere and positive correlation in the northern hemisphere. At the onset of the solar cycle, this hemispheric delineation pattern was prevalent, however, an inverse hemispheric delineation was observed at the recession of the solar cycle.

Investigation of Forbush Decreases and Other Solar/Geophysical Agents Associated With Lightning Over the U.S. Latitude Band and the Continental Africa
O. **Okike**
JGR Volume124, Issue6 June **2019** Pages 3910-3925
sci-hub.se/10.1029/2018JA026456
Regardless of the numerous significant contributions in the field (e.g., Svensmark, H. & Svensmark, J., 2009, https://doi.org/10.1029/2009GL038429; Svensmark, J., et al, 2012, https://doi.org/10.5194/acpd-12-3595-2012), the impact of cosmic rays on Earth's weather is still a source of misunderstanding among scientists. Chree method of analysis (Chree, 1912, https://doi.org/10.1098/rsta.1913.0003) is one of the commonest tool used in the investigation. But the method has been queried by some publications. Greater number of these critiques (Forbush et al., 1983, https://doi.org/10.1007/BF00145551; Prager & hoenig, 1989, https://doi.org/10.1577/1548-8659(1989)118<0608:SEAART>2.3.CO;2) (Forbush et al., 1983; Prager & Hoenig, 1989) point to the test of significance of epoch superposition results. Forbush events are the most widely key event time used in solar Earth's weather investigation. Despite the early indications of Marcz (1997, https://doi.org/10.1016/S1364-6826(96)00076-4) that the result of compositing analysis depends on the Forbush event selection criteria and timing, various conflicting methods of event selection still dominate articles documenting Forbush decrease (FD)-related correlations. The present submission calls the attention of researchers to the need for a systematic FD event identification with respect to timing and magnitude estimation prior to compositing/correlation/regression analyses. The relationship between program-selected FDs, World Wide Lightning Location Network (WWLLN) data, and

solar/geophysical parameters is tested at different regions of the world. Significant correlations between WWLLN and other parameters were observed at the U.S. latitude band and within the African region.

Estimating satellite orbital drag during historical magnetic superstorms

Denny M. **Oliveira** , Eftyhia Zesta , Hisashi Hayakawa , Ankush Bhaskar

Space Weather **Volume18, Issue11** e2020SW002472 **2020**

https://doi.org/10.1029/2020SW002472

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020SW002472

Understanding extreme space weather events is of paramount importance in efforts to protect technological systems in space and on the ground. Particularly in the thermosphere, the subsequent extreme magnetic storms can pose serious threats to low-Earth orbit (LEO) spacecraft by intensifying errors in orbit predictions. Extreme magnetic storms (minimum Dst ≤ ---250 nT) are extremely rare: only 7 events occurred during the era of spacecraft with high-level accelerometers such as CHAMP (CHAllenge Mini-satellite Payload) and GRACE (Gravity Recovery And Climate experiment), and none with minimum Dst ≤ --- 500 nT, here termed magnetic superstorms. Therefore, current knowledge of thermospheric mass density response to superstorms is very limited. Thus, in order to advance this knowledge, four known magnetic superstorms in history, i.e., events occurring before CHAMP's and GRACE's commission times, with complete datasets, are used to empirically estimate density enhancements and subsequent orbital drag. The November 2003 magnetic storm (minimum Dst = --- 422 nT), the most extreme event observed by both satellites, is used as the benchmark event. Results show that, as expected, orbital degradation is more severe for the most intense storms. Additionally, results clearly point out that the time duration of the storm is strongly associated with storm-time orbital drag effects, being as important as or even more important than storm intensity itself. The most extreme storm-time decays during CHAMP/GRACE-like sample satellite orbits estimated for the March 1989 magnetic superstorm show that long-lasting superstorms can have highly detrimental consequences for the orbital dynamics of satellites in LEO. **25 Sep 1909, 14-15 May 1921, 30 Oct-1 Nov 2003, 20 Nov 2003, 13 Mar 2009**

Satellite orbital drag during magnetic storms

D. M. **Oliveira** , E. Zesta

Space Weather v.17, #11, 1510-1533, **2019**

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019SW002287

We investigate satellite orbital drag effects at low-Earth orbit (LEO) associated with thermosphere heating during magnetic storms caused by coronal mass ejections. CHAllenge Mini-satellite Payload (CHAMP) and Gravity Recovery And Climate Experiment (GRACE) neutral density data are used to compute orbital drag. Storm-to-quiet density comparisons are performed with background densities obtained by the Jacchia-Bowman 2008 (JB2008) empirical model. Our storms are grouped in different categories regarding their intensities as indicated by minimum values of the SYM-H index. We then perform superposed epoch analyses with storm main phase onset as zero epoch time. In general, we find that orbital drag effects are larger for CHAMP (lower altitudes) in comparison to GRACE (higher altitudes). Results show that storm-time drag effects manifest first at high latitudes, but for extreme storms particularly observed by GRACE stronger orbital drag effects occur during early main phase at low/equatorial latitudes, probably due to heating propagation from high latitudes. We find that storm-time orbital decay along the satellites' path generally increases with storm intensity, being stronger and faster for the most extreme events. For these events, orbital drag effects decrease faster probably due to elevated cooling effects caused by nitric oxide, which introduce modeled density uncertainties during storm recovery phase. Errors associated with total orbit decay introduced by JB2008 are generally the largest for the strongest storms, and increase during storm times, particular during recovery phases. We discuss the implication of these uncertainties for the prediction of collision between space objects at LEO during magnetic storms. **24 August 2005, 20 November 2003**

Geomagnetically Induced Currents Caused by Interplanetary Shocks With Different Impact Angles and Speeds

D. M. **Oliveira** , D. Arel , J. Raeder, E. Zesta , C. M. Ngwira , B. A. Carter , E. Yizengaw , A. J. Halford , B. T. Tsurutani , J. W. Gjerloev

Space Weather Volume16, Issue6, June **2018**, Pages 636-647

http://sci-hub.tw/10.1029/2018SW001880

The occurrence of geomagnetically induced currents (GICs) poses serious threats to modern technological infrastructure. Large GICs result from sharp variations of the geomagnetic field (dB/dt) caused by changes of large-scale magnetospheric and ionospheric currents. Intense dB/dt perturbations are known to occur often in high-latitude regions as a result of storm time substorms. Magnetospheric compressions usually caused by

interplanetary shocks increase the magnetopause current leading to dB/dt perturbations more evident in midlatitude to low-latitude regions, while they increase the equatorial electrojet current leading to dB/dt perturbations in dayside equatorial regions. We investigate the effects of shock impact angles and speeds on the subsequent dB/dt perturbations with a database of 547 shocks observed at the L1 point. By adopting the threshold of dB/dt = 100 nT/min, identified as a risk factor to power systems, we find that dB/dt generally surpasses this threshold when following impacts of high-speed and nearly frontal shocks in dayside high-latitude locations. The same trend occurs at lower latitudes and for all nightside events but with fewer high-risk events. Particularly, we found nine events in equatorial locations with dB/dt > 100 nT/min. All events were caused by high-speed and nearly frontal shock impacts and were observed by stations located around noon local time. These high-risk perturbations were caused by sudden strong and symmetric magnetospheric compressions, more effectively intensifying the equatorial electrojet current, leading to sharp dB/dt perturbations. We suggest that these results may provide insights for GIC forecasting aiming at preventing degradation of power systems due to GICs.

Assessment and recommendations for a consolidated European approach to space weather – as part of a global space weather effort

Hermann J. **Opgenoorth**1,8*, Robert F. Wimmer-Schweingruber2, Anna Belehaki4, David Berghmans3, Mike Hapgood5, Michael Hesse6, Kirsti Kauristie7, Mark Lester8, Jean Lilensten9, Mauro Messerotti10,11 and Manuela Temmer12

J. Space Weather Space Clim., 9, A37, **2019**

https://www.swsc-journal.org/articles/swsc/pdf/2019/01/swsc190036.pdf

Over the last 10–20 years there has been an ever-increasing international awareness of risks to modern society from adverse and potentially harmful – and in extreme cases even disastrous – space weather events. Many individual countries and even international organisations like the United Nations (UN) have begun to increase their activities in preparing for and mitigating effects of adverse space weather. As in the rest of the world there is also in Europe an urgent need for coordination of Space Weather efforts in individual countries as well as in and among European organisations such as the European Space Agency (ESA) and the European Union (EU). This coordination should not only improve our ability to meet space weather risks, but also enable Europe to contribute to on-going global space weather efforts. While space weather is a global threat, which needs a global response, it also requires tailored regional and trans-regional responses that require coordination at all levels. Commissioned by the European Space Science Committee (ESSC) of the European Science Foundation, the authors – together with ex-officio advice from ESA and the EU – have over two years assessed European activities in the realm of space weather and formulated a set of recommendations to ESA, the EU and their respective member states, about how to prepare Europe for the increasing impact of adverse space weather effects on man-made infrastructure and our society as a whole. We have also analysed parallel international activities worldwide, and we give advice how Europe could incorporate its future activities into a global scheme.

A regional space weather hazard variation index utilising Swarm FAST data

Lauren **Orr***, Ciarán Beggan and William Brown

J. Space Weather Space Clim. **2024**, 14, 30

https://www.swsc-journal.org/articles/swsc/pdf/2024/01/swsc240028.pdf

We develop a new method for the determination of a regional hazard indicator using Swarm satellite near-real-time Fast Track (‘FAST’) data based on pre-computed threshold exceedances. The European Space Agency (ESA) aim to deliver the FAST data promptly (currently twice daily) compared to the standard four-day lag with Swarm operational (‘OPER’) data. This provides an opportunity to map localized intense field variation during geomagnetic storms in areas without fixed ground-based magnetometers. To determine the location-dependent threshold above which we consider the magnetic field to be highly active, we compute the 20-s standard deviation of the magnetic field along the track and create baseline thresholds derived from 10 years of Swarm data. Using the standard 1 Hz Level1b LR MAG product, we first remove models of the core, crust and magnetosphere before analysing the ionospheric residuals to determine geomagnetically quiet and active thresholds. We bin the residuals into 20,840 quasi-uniform grid cells globally and compute the typical magnetic field variance expected in each cell. From the binned magnetic variances, we can determine thresholds for exceedance e.g. at the 99th percentile in each grid cell. If the value of the magnetic variation computed from Swarm FAST data, using the same method, exceeds the pre-determined thresholds within the bin, this indicates a highly variable magnetic field in the region, implying a localized increase in space weather hazard risk in regions without ground observatories. We present our Swarm-specific index which we can compare to other geomagnetic indices such as Kp. Our index compares well to Kp and the higher-cadence Hp60 and captures activity levels during both geomagnetic storms and quiet times. Using FAST data, we can quickly quantify the hazard on a per-orbit (or shorter) basis, thus providing as close to real-time geomagnetic activity monitoring as presently feasible. The methodology can also be used by other satellite missions surveying magnetic fields.

Wavelet and Network Analysis of Magnetic Field Variation and Geomagnetically Induced Currents During Large Storms

L. **Orr**, S. C. Chapman, C. D. Beggan

Space Weather Volume19, Issue9 e2021SW002772 **2021**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021SW002772
https://doi.org/10.1029/2021SW002772

During geomagnetic storms rapid magnetic variations cause large, sharp enhancements of the magnetic and geoelectric field at mid-latitudes. These present a potential hazard to grounded technology such as high voltage transformers, pipelines and railway systems. Spatiotemporal quantification can provide insight into the magnitude and configuration of their potential hazard. We use the Haar wavelet transform to localize in time and frequency the storm-time response in both European ground-based magnetometer measurements and modeled geomagnetically induced currents (GICs) from the high voltage grid of Great Britain (GB). Wavelet cross-correlation of the GIC in the grounded nodes is then used to build a time-varying network of GIC flow around the GB grid during storms including the **2003 Halloween storm**. We find a highly intermittent (few tens of minutes duration) long-range coherent response that can span the entire physical grid at most intense times. The spatial pattern of response seen in the GIC flow network does not simply follow that of the amplitude of the rate of change of B field. Coherent response is excited across spatially extended clusters comprised of a subset of nodes that are highly connected to each other, with a tendency for east-west linkages following that of the physical grid, simultaneous with the overhead presence of the auroral electrojet and the inducing component of the magnetic field. This can quantify the spatial and temporal location of increased hazard in specific regions during large storms by including effects of both the geophysical and engineering configuration of the high voltage grid.

Quantifying the daily economic impact of extreme space weather due to failure in electricity transmission infrastructure

Edward J. **Oughton**, Andrew Skelton, Richard B. Horne, Alan W. P. Thomson, Charles T. Gaunt

Space Weather Volume 15, Issue 1 January **2017** Pages 65–83
http://sci-hub.cc/doi/10.1002/2016SW001491

Extreme space weather due to coronal mass ejections has the potential to cause considerable disruption to the global economy by damaging the transformers required to operate electricity transmission infrastructure. However, expert opinion is split between the potential outcome being one of a temporary regional blackout and of a more prolonged event. The temporary blackout scenario proposed by some is expected to last the length of the disturbance, with normal operations resuming after a couple of days. On the other hand, others have predicted widespread equipment damage with blackout scenarios lasting months. In this paper we explore the potential costs associated with failure in the electricity transmission infrastructure in the U.S. due to extreme space weather, focusing on daily economic loss. This provides insight into the direct and indirect economic consequences of how an extreme space weather event may affect domestic production, as well as other nations, via supply chain linkages. By exploring the sensitivity of the blackout zone, we show that on average the direct economic cost incurred from disruption to electricity represents only 49% of the total potential macroeconomic cost. Therefore, if indirect supply chain costs are not considered when undertaking cost-benefit analysis of space weather forecasting and mitigation investment, the total potential macroeconomic cost is not correctly represented. The paper contributes to our understanding of the economic impact of space weather, as well as making a number of key methodological contributions relevant for future work. Further economic impact assessment of this threat must consider multiday, multiregional events.

Extreme Space-Weather Events and the Solar Cycle

Mathew J. **Owens**, Mike Lockwood,Luke A. Barnard,Chris J. Scott, Carl Haines & Allan Macneil

Solar Physics volume 296, Article number: 82 (**2021**)
https://link.springer.com/content/pdf/10.1007/s11207-021-01831-3.pdf
https://doi.org/10.1007/s11207-021-01831-3

Space weather has long been known to approximately follow the solar cycle, with geomagnetic storms occurring more frequently at solar maximum than solar minimum. There is much debate, however, about whether the most hazardous events follow the same pattern. Extreme events – by definition – occur infrequently, and thus establishing their occurrence behaviour is difficult even with very long space-weather records. Here we use the 150-year aaHaaH record of global geomagnetic activity with a number of probabilistic models of geomagnetic-storm occurrence to test a range of hypotheses. We find that storms of all magnitudes occur more frequently during an active phase, centred on solar maximum, than during the quiet phase around solar minimum. We also show that the available observations are consistent with the most extreme events occurring more frequently during large solar cycles than small cycles. Finally, we report on the difference in extreme-event occurrence during odd- and even-numbered solar cycles, with events clustering earlier in even cycles and later in odd cycles. Despite the relatively few events available for study, we demonstrate that this is inconsistent with random occurrence. We interpret this finding in terms of the overlying coronal magnetic field and enhanced magnetic-field strengths in the heliosphere, which act to increase the geoeffectiveness of sheath regions ahead of extreme coronal mass ejections. Putting the

three "rules" together allows the probability of extreme event occurrence for Solar Cycle 25 to be estimated, if the magnitude and length of the coming cycle can be predicted. This highlights both the feasibility and importance of solar-cycle prediction for planning and scheduling of activities and systems that are affected by extreme space weather.

Near-Earth solar wind forecasting using corotation from L5: The error introduced by heliographic latitude offset

M.J. **Owens**, P. Riley, M. Lang, M. Lockwood
Space Weather **2019**
https://doi.org/10.1029/2019SW002204
Routine in-situ solar wind observations from L5, located 60° behind Earth in its orbit, would provide a valuable input to space-weather forecasting. One way to ulitise such observations is to assume that the solar wind is in perfect steady state over the 4.5 days it takes the Sun to rotate 60° and thus near-Earth solar wind in 4.5-days time would be identical to that at L5 today. This corotation approximation is most valid at solar minimum when the solar wind is slowly evolving. Using STEREO data, it has been possible to test L5-corotation forecasting for a few months at solar minimum, but the various contributions to forecast error cannot be disentangled. This study uses 40+ years of magnetogram-constrained solar wind simulations to isolate the effect of latitudinal offset between L5 and Earth due to the inclination of the ecliptic plane to the solar rotational equator. Latitudinal offset error is found to be largest at solar minimum, due to the latitudinal ordering of solar wind structure. It is also a strong function of time of year; maximum at the solstices and very low at equinoxes. At solstice, the latitudinal offset alone means L5-corotation forecasting is expected to be less accurate than numerical solar wind models, even before accounting for time-dependent solar wind structures. Thus, a combination of L5-corotation and numerical solar wind modelling may provide the best forecast. These results also highlight that three-dimensional solar wind structure must be accounted for when performing solar wind data assimilation.

Time-Window Approaches to Space-Weather Forecast Metrics: A Solar Wind Case Study

Mathew J. **Owens**
Space Weather Volume16, Issue11 November **2018** Pages 1847-1861
http://sci-hub.tw/10.1029/2018SW002059
Metrics are an objective, quantitative assessment of forecast (or model) agreement with observations. They are essential for assessing forecast accuracy and reliability and consequently act as a diagnostic for forecast development. Partly as a result of limited spatial sampling of observations, much of space-weather forecasting is focused on the time domain rather than inherent spatial variability. Thus, metrics are primarily point-by-point approaches, in which observed conditions at time t are compared directly (and only) with the forecast conditions at time t. Such metrics are undoubtedly useful. But in lacking an explicit consideration of timing uncertainties, they have limitations as diagnostic tools and can, under certain conditions, be misleading. Using a near-Earth solar wind speed forecast as an illustrative example, this study briefly reviews the most commonly used point-by-point metrics and advocates for complementary time window approaches. In particular, a scale-selective approach, originally developed in numerical weather prediction for validation of spatially patchy rainfall forecasts, is adapted to the time domain for space-weather purposes. This simple approach readily determines the time scales over which a forecast is and is not valuable, allowing the results of point-by-point metrics to be put in greater context. **20 Oct-12 Nov 2006**

Ion Charge States and Potential Geoeffectiveness: The Role of Coronal Spectroscopy for Space-Weather Forecasting

M. J. **Owens** M. Lockwood L. A. Barnard
Space Weather Volume16, Issue6 June **2018** Pages 694-703
http://sci-hub.tw/10.1029/2018SW001855
Severe space weather is driven by interplanetary coronal mass ejections (ICMEs), episodic eruptions of solar plasma, and magnetic flux that travel out through the heliosphere and can perturb the Earth's magnetosphere and ionosphere. In order for space-weather forecasts to allow effective mitigating action, forecasts must be made as early as possible, necessitating identification of potentially "geoeffective" ICMEs close to the Sun. This presents two challenges. First, geoeffectiveness is primarily determined by the magnetic field intensity and orientation, both of which are difficult to measure close to the Sun. Second, the magnetic field evolves in transit between the Sun and the Earth, sometimes in a highly nonlinear way. Conversely, solar wind ion charge states, such as the ratio of O^{7+} to O^{6+}, are fixed by the electron temperature at the coronal height where ion-electron collisions are last possible as the ICME erupts. After this point, they are said to be "frozen in" as they do not evolve further as the ICME propagates through the solar wind. In this study we show that ion charge states, while not geoeffective in and of themselves, act as strong markers for the geoeffectiveness of the ICME. The probability of severe space weather is around 7 times higher in "hot" ICMEs than "cold" ICMEs, as defined by O^{7+}/O^{6+}. We suggest that coronal spectroscopy of

ICMEs could complement current forecasting techniques, providing valuable additional information about potential geoeffectiveness.

Probabilistic Solar Wind Forecasting Using Large Ensembles of Near-Sun Conditions With a Simple One-Dimensional "Upwind" Scheme

Mathew J. **Owens**, Pete Riley

Space Weather November **2017** Vol: 15, Pages: 1461–1474

http://onlinelibrary.wiley.com/doi/10.1002/2017SW001679/full

Long lead-time space-weather forecasting requires accurate prediction of the near-Earth solar wind. The current state of the art uses a coronal model to extrapolate the observed photospheric magnetic field to the upper corona, where it is related to solar wind speed through empirical relations. These near-Sun solar wind and magnetic field conditions provide the inner boundary condition to three-dimensional numerical magnetohydrodynamic (MHD) models of the heliosphere out to 1 AU. This physics-based approach can capture dynamic processes within the solar wind, which affect the resulting conditions in near-Earth space. However, this deterministic approach lacks a quantification of forecast uncertainty. Here we describe a complementary method to exploit the near-Sun solar wind information produced by coronal models and provide a quantitative estimate of forecast uncertainty. By sampling the near-Sun solar wind speed at a range of latitudes about the sub-Earth point, we produce a large ensemble (N = 576) of time series at the base of the Sun-Earth line. Propagating these conditions to Earth by a three-dimensional MHD model would be computationally prohibitive; thus, a computationally efficient one-dimensional "upwind" scheme is used. The variance in the resulting near-Earth solar wind speed ensemble is shown to provide an accurate measure of the forecast uncertainty. Applying this technique over 1996–2016, the upwind ensemble is found to provide a more "actionable" forecast than a single deterministic forecast; potential economic value is increased for all operational scenarios, but particularly when false alarms are important (i.e., where the cost of taking mitigating action is relatively large).

Probabilistic Solar Wind and Geomagnetic Forecasting Using an Analogue Ensemble or "Similar Day" Approach

M. J. **Owens**, P. Riley, T. S. Horbury

Solar Physics May **2017**, 292:69

http://link.springer.com/content/pdf/10.1007%2Fs11207-017-1090-7.pdf

Effective space-weather prediction and mitigation requires accurate forecasting of near-Earth solar-wind conditions. Numerical magnetohydrodynamic models of the solar wind, driven by remote solar observations, are gaining skill at forecasting the large-scale solar-wind features that give rise to near-Earth variations over days and weeks. There remains a need for accurate short-term (hours to days) solar-wind forecasts, however. In this study we investigate the analogue ensemble (AnEn), or "similar day", approach that was developed for atmospheric weather forecasting. The central premise of the AnEn is that past variations that are analogous or similar to current conditions can be used to provide a good estimate of future variations. By considering an ensemble of past analogues, the AnEn forecast is inherently probabilistic and provides a measure of the forecast uncertainty. We show that forecasts of solar-wind speed can be improved by considering both speed and density when determining past analogues, whereas forecasts of the out-of-ecliptic magnetic field [\(B_{\mathrm{N}}\)] are improved by also considering the in-ecliptic magnetic-field components. In general, the best forecasts are found by considering only the previous 6 – 12 hours of observations. Using these parameters, the AnEn provides a valuable probabilistic forecast for solar-wind speed, density, and in-ecliptic magnetic field over lead times from a few hours to around four days. For \(B_{\mathrm{N}}\), which is central to space-weather disturbance, the AnEn only provides a valuable forecast out to around six to seven hours. As the inherent predictability of this parameter is low, this is still likely a marked improvement over other forecast methods. We also investigate the use of the AnEn in forecasting geomagnetic indices Dst and Kp. The AnEn provides a valuable probabilistic forecast of both indices out to around four days. We outline a number of future improvements to AnEn forecasts of near-Earth solar-wind and geomagnetic conditions.

Ensemble downscaling in coupled solar wind-magnetosphere modeling for space weather forecasting,

Owens, M. J., T. S. Horbury, R. T. Wicks, S. L. McGregor, N. P. Savani, and M. Xiong (**2014**),*Space Weather*, *12*, 395–405, doi:10.1002/2014SW001064.

The Heliospheric Magnetic Field **Review**

Owens, Mathew J. and Forsyth, Robert J.

Living Reviews in Solar Physics, PUB.NO. lrsp-**2013**-5

http://www.livingreviews.org/lrsp-2013-5

The heliospheric magnetic field (HMF) is the extension of the coronal magnetic magnetic carried by the solar wind. It is the means by which the Sun interacts with planetary magnetospheres and channels charged particles propagating through the heliosphere. As the HMF remains rooted at the solar photosphere as the Sun rotates, the large-scale HMF traces out an Archimedean spiral. This pattern is distorted by the the interaction of fast and slow solar wind streams, as well as the interplanetary manifestations of coronal mass ejections. On the smaller scale, the HMF exhibits an array of waves, discontinuities and turbulence, which give hints to the solar wind formation process. This review aims to summarise observations and theory of the small- and large-scale structure of the HMF. Solar-cycle and cycle-to-cycle evolution of the HMF is discussed in terms of recent spacecraft observations and pre-spaceage proxies for the HMF in geomagnetic and galactic cosmic ray records.

A 27 day persistence model of near-Earth solar wind conditions: A long lead-time forecast and a benchmark for dynamical models.

Owens, M.J., Challen, R., Methven, J., Henley, E., Jackson, D.R.:
2013, Space Weather 11(5), 225.
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/swe.20040

Geomagnetic activity has long been known to exhibit approximately 27 day periodicity, resulting from solar wind structures repeating each solar rotation. Thus a very simple near-Earth solar wind forecast is 27 day persistence, wherein the near-Earth solar wind conditions today are assumed to be identical to those 27 days previously. Effective use of such a persistence model as a forecast tool, however, requires the performance and uncertainty to be fully characterized. The first half of this study determines which solar wind parameters can be reliably forecast by persistence and how the forecast skill varies with the solar cycle. The second half of the study shows how persistence can provide a useful benchmark for more sophisticated forecast schemes, namely physics-based numerical models. Point-by-point assessment methods, such as correlation and mean-square error, find persistence skill comparable to numerical models during solar minimum, despite the 27 day lead time of persistence forecasts, versus 2–5 days for numerical schemes. At solar maximum, however, the dynamic nature of the corona means 27 day persistence is no longer a good approximation and skill scores suggest persistence is out-performed by numerical models for almost all solar wind parameters. But point-by-point assessment techniques are not always a reliable indicator of usefulness as a forecast tool. An event-based assessment method, which focusses key solar wind structures, finds persistence to be the most valuable forecast throughout the solar cycle. This reiterates the fact that the means of assessing the “best” forecast model must be specifically tailored to its intended use.

Metrics for solar wind prediction models: Comparison of empirical, hybrid, and physics-based schemes with 8 years of L1 observations

Owens, M. J.; Spence, H. E.; McGregor, S.; Hughes, W. J.; Quinn, J. M.; Arge, C. N.; Riley, P.; Linker, J.; Odstrcil, D.
Space Weather, Vol. 6, No. 8, S08001, **2008**
10.1029/2007SW000380

To calculate performance metrics for a variety of models developed by the Center for Integrated Space Weather Modeling, a scientist presents results of modeling solar corona-heliosphere processes and their ability to predict solar wind conditions at the L1 Lagrangian point upstream of Earth.

Temporal Offsets between Maximum CME Speed Index and Solar, Geomagnetic, and Interplanetary Indicators during Solar Cycle 23 and the Ascending Phase of Cycle 24

A. **Özgüç**, A. Kilcik, K. Georgieva, B. Kirov
Solar Phys. Volume 291, Issue 5, pp 1533-1546 **2016**
https://arxiv.org/ftp/arxiv/papers/1604/1604.05941.pdf

On the basis of morphological analysis of yearly values of the maximum CME (coronal mass ejection) speed index, the sunspot number and total sunspot area, sunspot magnetic field, and solar flare index, the solar wind speed and interplanetary magnetic field strength, and the geomagnetic Ap and Dst indices, we point out the particularities of solar and geomagnetic activity during the last cycle 23, the long minimum which followed it and the ascending branch of cycle 24. We also analyze temporal offset between the maximum CME speed index and the above-mentioned solar, geomagnetic, and interplanetary indices. It is found that this solar activity index, analyzed jointly with other solar activity, interplanetary parameters, and geomagnetic activity indices, shows a hysteresis phenomenon. It is observed that these parameters follow different paths for the ascending and the descending phases of solar cycle 23. It is noticed that the hysteresis phenomenon represents a clue in the search for physical processes responsible for linking the solar activity to the near-Earth and geomagnetic responses.

A new technique for observationally derived boundary conditions for space weather

P. **Pagano**, D.H. Mackay, A.R. Yeates
Journal of Space Weather and Space Climate 8, A26 **2018**
https://arxiv.org/pdf/1802.07516.pdf
https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc170023.pdf

Context. In recent years, space weather research has focused on developing modelling techniques to predict the arrival time and properties of coronal mass ejections (CMEs) at the Earth. The aim of this paper is to propose a new modelling technique suitable for the next generation of Space Weather predictive tools that is both efficient and accurate. The aim of the new approach is to provide interplanetary space weather forecasting models with accurate time dependent boundary conditions of erupting magnetic flux ropes in the upper solar corona.
Methods. To produce boundary conditions, we couple two different modelling techniques, MHD simulations and a quasi-static non-potential evolution model. Both are applied on a spatial domain that covers the entire solar surface, although they extend over a different radial distance. The non-potential model uses a time series of observed synoptic magnetograms to drive the non-potential quasi-static evolution of the coronal magnetic field. This allows us to follow the formation and loss of equilibrium of magnetic flux ropes. Following this a MHD simulation captures the dynamic evolution of the erupting flux rope, when it is ejected into interplanetary space.
Results.The present paper focuses on the MHD simulations that follow the ejection of magnetic flux ropes to 4 R⊙. We first propose a technique for specifying the pre-eruptive plasma properties in the corona. Next, time dependent MHD simulations describe the ejection of two magnetic flux ropes, that produce time dependent boundary conditions for the magnetic field and plasma at 4 R⊙ that in future may be applied to interplanetary space weather prediction models.
Conclusions. In the present paper, we show that the dual use of quasi-static non-potential magnetic field simulations and full time dependent MHD simulations can produce realistic inhomogeneous boundary conditions for space weather forecasting tools. Before a fully operational model can be produced there are a number of technical and scientific challenges that still need to be addressed. Nevertheless, we illustrate that coupling quasi-static and MHD simulations in this way can significantly reduce the computational time required to produce realistic space weather boundary conditions.

The Spanish Space Weather Service SeNMEs. A case study on the Sun-Earth chain

J. **Palacios**, C. Cid, A. Guerrero, E. Saiz, Y. Cerrato, M. Rodríguez-Bouza, I. Rodríguez-Bilbao, M. Herraiz, G. Rodríguez-Caderot

ASP Conference Series, **2016**, volume 504: Ground based solar observations in the space instrumentation era **2017**
https://arxiv.org/pdf/1704.00684.pdf

The Spanish Space Weather Service SeNMEs, \url{www.senmes.es}, is a portal created by the SRG-SW of the Universidad de Alcal\'a, Spain, to meet societal needs of near real-time space weather services. This webpage-portal is divided in different sections to fulfill users needs about space weather effects: radio blackouts, solar energetic particle events, geomagnetic storms and presence of geomagnetically induced currents. In less than one year of activity, this service has released a daily report concerning the solar current status and interplanetary medium, informing about the chances of a solar perturbation to hit the Earth's environment. There are also two different forecasting tools for geomagnetic storms, and a daily ionospheric map. These tools allow us to nowcast a variety of solar eruptive events and forecast geomagnetic storms and their recovery, including a new local geomagnetic index, LDi{\~n}, along with some specific new scaling. In this paper we also include a case study analysed by SeNMEs. Using different high resolution and cadence data from space-borne solar telescopes SDO, SOHO and GOES, along with ionospheric and geomagnetic data, we describe the Sun-Earth feature chain for the event. **22-23 June 2015**

Chapter 13 - Near-Earth Radiation Environment for Extreme Solar and Geomagnetic Conditions **Review**

Mikhail **Panasyuk***†VladimirKalegaev*LeontyMiroshnichenko*‡NikolayKuznetsov*RikhoNymmik*HelenPopova*BorisYushkov*VictorBenghin

In: Extreme Events in Geospace Origins, Predictability, and Consequences **2018**, Pages 349-372
http://sci-hub.tw/10.1016/B978-0-12-812700-1.00013-3

The near-Earth environment can be considered a unique place where different space radiation fields exist and can play a significant role in the estimation of radiation risks both for robotic and manned space missions. One cannot exclude the cumulative effect for particular spacecraft orbits the result of simultaneous impact of the different radiation fields. Among the types of space radiation, we consider: trapped radiation at low Earth orbits (LEO): solar energetic particles (SEP) penetration in the magnetosphere, including ground level enhancement events (GLE); and variations of galactic cosmic rays (GCR) during the different extreme levels of geomagnetic and solar activity. Results of empirical modeling of these different radiation fields and some results of measurements of their physical parameters (energy spectra, space and time variations) for different solar (extreme solar maxima and solar minima) and geomagnetic (the major magnetic storms) conditions are analyzed. The models are based on quantitative relationships between the particle fluxes, taking into account the solar activity (sunspot numbers). Examples of using these models to estimate changes of radiation hazards in interplanetary space for the possible case of solar activity reduction during the nearest solar cycles 25 and 26 are analyzed. **March 7–11, 2012**

Table 1 The Large Solar Proton Events Dose Onboard the ISS and MIR Space Station

Space Weather: Russian Perspectives

M. **Panasyuk**

Space Weather Geophysical Monograph 125, **2001 File**

Different scientific groups in Russia are successfully developing the complex of experiments and models directed to Space Weather problems. At present the complex consists of the following major parts: optics and radio observations of the Sun and a forecasting model of large solar flares; ground based monitoring of the heliospheric (neutron monitors) and geomagnetic (magnetometers) conditions; models of the geomagnetic storm forecasting; a model of galactic cosmic rays and a probabilistic model of solar energetic particles; monitoring of the radiation environment by satellites. The problems of compilation of these parts and perspectives of their future development are discussed.

Solar Activities and Its Impact on Space Weather

Pandit, Drabindra; Chapagain, Narayan P.; Adhikari, Binod; Mishra, Roshan K.

Long-term Datasets for the Understanding of Solar and Stellar Magnetic Cycles, Proceedings of the International Astronomical Union, IAU Symposium, Volume 340, pp. 149-150, **2018**

sci-hub.se/10.1017/S1743921318001606

The Sun is an active star and its magnetic field fluctuates from a fraction of a second to a long period of time. The solar wind, CME, solar prominence, solar flares, solar particle and solar filament are the direct result of solar magnetic activity effects on the interplanetary space, Earth's magnetosphere and ionosphere. The intensity of irruption of these phenomena from the Sun's surface depends upon its phases. The extreme events affect technology both in space and on the ground.The data obtained from series of observations can help to predict solar activities and safekeeping to the space technology. In this study the cross correlations between IMF Bz, solar wind velocity(Vsw) and interplanetary electric field(Ey) with AE and SYM-H are studied. The results reveal that strong geomagnetic disturbances have high impact on the components of space weather than weak disturbances have. **17 March 2015, 22 June 2015**

Effective Acceleration Model for the Arrival Time of Interplanetary Shocks driven by Coronal Mass Ejections

Evangelos **Paouris**, Helen Mavromichalaki

Solar Physics December **2017**, 292:180

https://link.springer.com/content/pdf/10.1007%2Fs11207-017-1212-2.pdf

In a previous work (Paouris and Mavromichalaki in Solar Phys. 292, 30, 2017), we presented a total of 266 interplanetary coronal mass ejections (ICMEs) with as much information as possible. We developed a new empirical model for estimating the acceleration of these events in the interplanetary medium from this analysis. In this work, we present a new approach on the effective acceleration model (EAM) for predicting the arrival time of the shock that preceds a CME, using data of a total of 214 ICMEs. For the first time, the projection effects of the linear speed of CMEs are taken into account in this empirical model, which significantly improves the prediction of the arrival time of the shock. In particular, the mean value of the time difference between the observed time of the shock and the predicted time was equal to +3.03 hours with a mean absolute error (MAE) of 18.58 hours and a root mean squared error (RMSE) of 22.47 hours. After the improvement of this model, the mean value of the time difference is decreased to −0.28 hours with an MAE of 17.65 hours and an RMSE of 21.55 hours. This improved version was applied to a set of three recent Earth-directed CMEs reported in May, June, and July of 2017, and we compare our results with the values predicted by other related models. **23 May, 28 June, and 14 July 2017**

Interplanetary Coronal Mass Ejections Resulting from Earth-Directed CMEs Using SOHO and ACE Combined Data During Solar Cycle 23

Evangelos **Paouris**, Helen Mavromichalaki

Solar Physics February **2017**, 292:30 **File**

http://cosray.phys.uoa.gr/publications/D115.pdf

In this work a total of 266 interplanetary coronal mass ejections observed by the Solar and Heliospheric Observatory/Large Angle and Spectrometric Coronagraph (SOHO/LASCO) and then studied by in situ observations from Advanced Composition Explorer (ACE) spacecraft, are presented in a new catalog for the time interval 1996 – 2009 covering Solar Cycle 23. Specifically, we determine the characteristics of the CME which is responsible for the upcoming ICME and the associated solar flare, the initial/background solar wind plasma and magnetic field conditions before the arrival of the CME, the conditions in the sheath of the ICME, the main part of the ICME, the geomagnetic conditions of the ICME's impact at Earth and finally we remark on the visual examination for each event. Interesting results revealed from this study include the high correlation coefficient values of the magnetic field \(B_{z}\) component against the Ap index (\(r = 0.84\)), as well as against the Dst index (\(r = 0.80\)) and of

the effective acceleration against the CME linear speed ($r = 0.98$). We also identify a north–south asymmetry for X-class solar flares and an east–west asymmetry for CMEs associated with strong solar flares (magnitude ≥ M1.0) which finally triggered intense geomagnetic storms (with $\mathrm{Ap} \geq 179$). The majority of the geomagnetic storms are determined to be due to the ICME main part and not to the extreme conditions which dominate inside the sheath. For the intense geomagnetic storms the maximum value of the Ap index is observed almost 4 hours before the minimum Dst index. The amount of information makes this new catalog the most comprehensive ICME catalog for Solar Cycle 23. **6 November 2000**
There are many **ICME catalogs** which contain useful information
as regards these events, such as those by Jian *et al.* (2006), Richardson and
Cane (2010), Gopalswamy *et al.* (2010), Mitsakou and Moussas (2014) or more recently
Chi *et al.* (2016). A comprehensive list of different ICME catalogs can be found at
http://solar.gmu.edu/heliophysics/index.php/The_ISEST_ICME%5CCME_Lists or the ISEST
Master CME list at http://solar.gmu.edu/heliophysics/index.php/The_ISEST_Master_CME_List.

Nowcasting of Solar Energetic Particle Events using near real-time Coronal Mass Ejection characteristics in the framework of the FORSPEF tool

Athanasios **Papaioannou**, Anastasios Anastasiadis, Ingmar Sandberg and Piers Jiggens
J. Space Weather Space Clim. **2018**, 8, A37
https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc170060.pdf
In this work the derived occurrence probability of solar energetic particle (SEP) events (i.e. proton events measured at Earth's position) and their peak fluxes and total fluences depending on coronal mass ejection (CME) parameters, i.e. linear speed (V) and the angular width (AW) are presented. A new SEP catalogue with associated CME data from 1997 to 2013 is utilized. It is found that the SEP probability strongly depends on the CME speed and the angular width as follows: The highest association (72.70%) is obtained for the full halo CMEs with $V \geq 1500$ km s−1 and the lowest association (0.7%) is found for the non halo CMEs with 400 km s−1 ≤ V ≤ 1000 km s−1. The SEP occurrence probabilities are different as much as 26 times according to the CME speed (V), comparing fast versus slow CMEs and 44 times according to the AW, comparing halo to non halo CMEs. Furthermore, linear regressions of the proton peak flux and integral fluence at several integral energy channels (E > 10 MeV, E > 30 MeV, E > 60 MeV, E > 100 MeV) were obtained. Our results, were used to build a module of an operational forecasting tool (i.e. FORecasting Solar Particle Events and Flares – FORSPEF, http://tromos.space.noa.gr/forspef/). This module performs nowcasting (short term forecasting) of SEP events using near real-time CME identifications obtained from CACTus (http://sidc.oma.be/cactus/). The outputs offered by the operational module of the tool to the end user (textural, pictorial, archived data) are presented. Finally, the validation of the system, in terms of archived data is described, in terms of categorical scores (Probability of Detection – POD and a False Alarm Rate – FAR).
Table 5. SEP CME list (04.2013–09.2015).

Solar flares, coronal mass ejections and solar energetic particle event characteristics

Athanasios **Papaioannou**1*, Ingmar Sandberg1, Anastasios Anastasiadis1, Athanasios Kouloumvakos2, Manolis K. Georgoulis3, Kostas Tziotziou1,3, Georgia Tsiropoula1, Piers Jiggens4 and Alain Hilgers
J. Space Weather Space Clim., 6, A42 (**2016**)
http://www.swsc-journal.org/articles/swsc/pdf/2016/01/swsc150076.pdf
A new catalogue of 314 solar energetic particle (SEP) events extending over a large time span from 1984 to 2013 has been compiled. The properties as well as the associations of these SEP events with their parent solar sources have been thoroughly examined. The properties of the events include the proton peak integral flux and the fluence for energies above 10, 30, 60 and 100 MeV. The associated solar events were parametrized by solar flare (SF) and coronal mass ejection (CME) characteristics, as well as related radio emissions. In particular, for SFs: the soft X-ray (SXR) peak flux, the SXR fluence, the heliographic location, the rise time and the duration were exploited; for CMEs the plane-of-sky velocity as well as the angular width were utilized. For radio emissions, type III, II and IV radio bursts were identified. Furthermore, we utilized element abundances of Fe and O. We found evidence that most of the SEP events in our catalogue do not conform to a simple two-class paradigm, with the 73% of them exhibiting both type III and type II radio bursts, and that a continuum of event properties is present. Although, the so-called hybrid or mixed events are found to be present in our catalogue, it was not possible to attribute each SEP event to a mixed/hybrid sub-category. Moreover, it appears that the start of the type III burst most often precedes the maximum of the SF and thus falls within the impulsive phase of the associated SF. At the same time, type III bursts take place within ≈5.22 min, on average, in advance from the time of maximum of the derivative of the SXR flux (Neupert effect). We further performed a statistical analysis and a mapping of the logarithm of the proton peak flux at E > 10 MeV, on different pairs of the parent solar source characteristics. This revealed correlations in 3-D space and demonstrated that the gradual SEP events that stem from the central part of the visible solar disk constitute a significant radiation risk. The velocity of the associated CMEs, as well as the SXR peak flux and fluence, are all

fairly significantly correlated to both the proton peak flux and the fluence of the SEP events in our catalogue. The strongest correlation to SEP characteristics is manifested by the CME velocity. **1986.02.14, 2000.07.14, 2003.10.26-28-29, 2003.11.02-04**

A Novel Forecasting System for Solar Particle Events and Flares (FORSPEF)

Papaioannou, A.; Anastasiadis, A.; Sandberg, I.; Georgoulis, M. K.; Tsiropoula, G.; Tziotziou, K.; Jiggens, P.; Hilgers, A.

Journal of Physics: Conference Series, Volume 632, Issue 1, article id. 012075 (**2015**).
http://sci-hub.tw/10.1088/1742-6596/632/1/012075
http://iopscience.iop.org/article/10.1088/1742-6596/632/1/012075/pdf

Solar Energetic Particles (SEPs) result from intense solar eruptive events such as solar flares and coronal mass ejections (CMEs) and pose a significant threat for both personnel and infrastructure in space conditions. In this work, we present FORSPEF (Forecasting Solar Particle Events and Flares), a novel dual system, designed to perform forecasting of SEPs based on forecasting of solar flares, as well as independent SEP nowcasting. An overview of flare and SEP forecasting methods of choice is presented. Concerning SEP events, we make use for the first time of the newly re-calibrated GOES proton data within the energy range 6.0-243 MeV and we build our statistics on an extensive time interval that includes roughly 3 solar cycles (1984-2013). A new comprehensive catalogue of SEP events based on these data has been compiled including solar associations in terms of flare (magnitude, location) and CME (width, velocity) characteristics.

Application of decision-making to a solar flare forecast in the cost-loss ratio situation

Jongyeob **Park**, Yong-Jae Moon, Seonghwan Choi, Ji-Hye Baek, Kyung-Suk Cho, Kangjin Lee
Space Weather Volume 15, Issue 5 May **2017** Pages 704–712
http://sci-hub.cc/10.1002/2016SW001532

The conventional skill scores for evaluating flare forecast models do not take into account the effect of various cost-loss ratios. For the first time, we have applied a decision-making based on skill scores to a flare forecast model in cost-loss ratio situations. For this study, we consider a flare forecast model which provides daily solar flare probabilities from 2011 to 2014. The skill scores are computed through contingency tables as a function of probability threshold (Pth) for the decision-making. A value score (VS) is calculated as a function of cost-loss ratio (C/L) and Pth,which are linearly correlated with each other. The maximum values of VS are 0.57, 0.37, and 0.61 for C-, M-, and X-class flare, respectively. We expect that this study would provide a guideline to determine C/L and Pth for the better decision-making in similar forecast models.

Influences of Space Weather Forecasting Uncertainty on Satellite Conjunction Assessment

William E. **Parker**, Mervyn Freeman, Gareth Chisham, Andrew Kavanagh, Peng Mun Siew, Victor Rodriguez-Fernandez, Richard Linares
Space Weather Volume22, Issue7 July **2024** e2023SW003818
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2023SW003818

A significant increase in the number of anthropogenic objects in Earth orbit has necessitated the development of satellite conjunction assessment and collision avoidance capabilities for new spacecraft. Neutral mass density variability in the thermosphere, driven by enhanced geomagnetic activity and solar EUV absorption, is a major source of satellite propagation error. This work investigates the impacts of space weather driver forecasting uncertainty on satellite drag and collision avoidance maneuver decision-making. Since most operational space weather driver forecasts do not offer an uncertainty assessment, the satellite operator community is left to make dangerous assumptions about the trustworthiness of the forecast models they use to perform satellite state propagation. Climatological persistence-based forecast models are developed for F10.7 and Kp. These models accurately capture the heteroscedastic and, at times, highly non-Gaussian uncertainty distribution on forecasts of the drivers of interest. A set of realistic satellite conjunction scenarios is simulated to demonstrate the contributions of space weather driver forecast uncertainty on the probability of collision and maneuver decisions. Improved driver forecasts, especially forecasts of F10.7, are demonstrated to be very useful for enabling durable maneuver decisions with additional lead time (up to 24 hr for the period examined), though the improvement depends on the specific conjunction scenario of interest.

An analytic review of geomagnetically induced current effects in power system.

Patel, K.J., Patel, J.A., Mehta, R.S., Rathod, S.B., Rajput, V.N., Pandya, K.S.: 2016,
In: International Conference on Electrical, Electronics, and Optimization Techniques, ICEEOT **2016**, 3906. DOI. ISBN 9781467399395.
sci-hub.se/10.1109/ICEEOT.2016.7755445

The Geomagnetically induced current (GIC) produces unwanted adverse consequences in the power system. It causes problems in the power system like transformer core saturation, really miss operation, blackout of system, voltage instability and heating of transformers, disturbance in communication systems, corrosion of pipelines, railway tracks etc. This paper provides information about GIC and its different effects in various technological systems. Also present the possible solution to reduce GIC.

Automated Solar Feature Detection for Space Weather Applications A Review

David **Perez-Suarez**, Paul A. Higgins, D. Shaun Bloomfield, R.T. James McAteer, Larisza D. Krista, Jason P. Byrne, Peter. T. Gallagher

E-print, Oct **2011**

Book chapter in -Applied Signal and Image Processing: Multidisciplinary Advancements- (ed. Rami Qahwaji, Roger Green and Evor L. Hines) pp. 207-225, 2011

http://arxiv.org/pdf/1109.6922v2.pdf

The solar surface and atmosphere are highly dynamic plasma environments, which evolve over a wide range of temporal and spatial scales. Large-scale eruptions, such as coronal mass ejections, can be accelerated to millions of kilometres per hour in a matter of minutes, making their automated detection and characterisation challenging. Additionally, there are numerous faint solar features, such as coronal holes and coronal dimmings, which are important for space weather monitoring and forecasting, but their low intensity and sometimes transient nature makes them problematic to detect using traditional image processing techniques. These difficulties are compounded by advances in ground- and space- based instrumentation, which have increased the volume of data that solar physicists are confronted with on a minute-by-minute basis; NASA's Solar Dynamics Observatory for example is returning many thousands of images per hour (~1.5 TB/day). *This chapter reviews recent advances in the application of images processing techniques to the automated detection of active regions, coronal holes, filaments, CMEs, and coronal dimmings for the purposes of space weather monitoring and prediction.* **2-Dec 2004**

COCONUT, a Novel Fast-converging MHD Model for Solar Corona Simulations. II. Assessing the Impact of the Input Magnetic Map on Space-weather Forecasting at Minimum of Activity

Barbara **Perri**1, Błażej Kuźma1, Michaela Brchnelova1, Tinatin Baratashvili1, Fan Zhang1, Peter Leitner2, Andrea Lani1, and Stefaan Poedts1,3

2023 ApJ 943 124

https://arxiv.org/pdf/2210.06165.pdf

https://iopscience.iop.org/article/10.3847/1538-4357/ac9799/pdf

This paper is dedicated to the new implicit unstructured coronal code COCONUT, which aims at providing fast and accurate inputs for space-weather forecasting as an alternative to empirical models. We use all 20 available magnetic maps of the solar photosphere covering the date of **2019 July 2**, which corresponds to a solar eclipse on Earth. We use the same standard preprocessing on all maps, then perform coronal MHD simulations with the same numerical and physical parameters. We conclude by quantifying the performance of each map using three indicators from remote-sensing observations: white-light total solar eclipse images for the streamers' edges, EUV synoptic maps for coronal holes, and white-light coronagraph images for the heliospheric current sheet. We discuss the performance of space-weather forecasting and show that the choice of the input magnetic map has a strong impact. We find performances between 24% and 85% for the streamers' edges, 24%–88% for the coronal hole boundaries, and a mean deviation between 4° and 12° for the heliospheric current sheet position. We find that the HMI runs perform better on all indicators, with GONG-ADAPT being the second-best choice. HMI runs perform better for the streamers' edges, and GONG-ADAPT for polar coronal holes, HMI synchronic for equatorial coronal holes, and the streamer belt. We especially illustrate the importance of the filling of the poles. This demonstrates that the solar poles have to be taken into account even for ecliptic plane previsions.

Comparing geosynchronous relativistic electron prediction models,

Perry, K. L., G. P. Ginet, A. G. Ling, and R. V. Hilmer

Space Weather, 8, S12002, (**2010**), doi:10.1029/2010SW000581.

Extended periods of relativistic electron intensity at geosynchronous orbit can create severe deep-charging hazards for satellites. Over the last 20 years a number of models have been developed to predict electron flux levels using solar wind and geomagnetic indices as inputs. We analyze the results of several of these including the Relativistic Electron Forecast Model based on the linear prediction filter technique, a neural network algorithm, and the physics-based diffusion method. Analyses using the methods of simple persistence and recurrence (based on the 27 day solar rotation) are also included as performance baselines. Comparisons are made to the GOES > 2 MeV electron flux to determine which model or method gives the best +1, +2, and +3 day forecasts of average daily flux during the interval 1996–2008. Model inputs include combinations of ΣKp, the daily average solar wind speed, and daily average > 2 MeV electron fluxes for one day or multiple days prior to the forecast days of interest. Prediction efficiencies are calculated for 6 month intervals. After evaluating all the models, there was no clear winner; each model did well at different phases of the solar cycle. All models perform their best during the inclining phase of solar minimum but not as well during solar maximum and the declining phase of solar minimum. While persistence is respectable for +1 day prediction, models clearly give superior +2 and +3 day predictions and should be used to obtain those forecasts.

Lessons learned from predictions of Solar Cycle 24

W. Dean **Pesnell***

J. Space Weather Space Clim. **2020**, 10, 60

https://doi.org/10.1051/swsc/2020060

https://www.swsc-journal.org/articles/swsc/pdf/2020/01/swsc200057.pdf

Solar Cycle 24 has almost faded and the activity of Solar Cycle 25 is appearing. We have learned much about predicting solar activity in Solar Cycle 24, especially with the data provided by SDO and STEREO. Many advances have come in the short-term predictions of solar flares and coronal mass ejections, which have benefited from applying machine learning techniques to the new data. The arrival times of coronal mass ejections is a mid-range prediction whose accuracy has been improving, mostly due to a steady flow of data from SoHO, STEREO, and SDO. Longer term (greater than a year) predictions of solar activity have benefited from helioseismic studies of the plasma flows in the Sun. While these studies have complicated the dynamo models by introducing more complex internal flow patterns, the models should become more robust with the added information. But predictions made long before a sunspot cycle begins still rely on precursors. The success of some categories of the predictions of Solar Cycle 24 will be examined. The predictions in successful categories should be emphasized in future work. The SODA polar field precursor method, which has accurately predicted the last three cycles, is shown for Solar Cycle 25. Shape functions for the sunspot number and F10.7 are presented. What type of data is needed to better understand the polar regions of the Sun, the source of the most accurate precursor of long-term solar activity, will be discussed.

Medium-term predictions of F10.7 and F30 cm solar radio flux with the adaptive Kalman filter

Elena **Petrova**, Tatiana Podladchikova, Astrid M. Veronig, Stijn Lemmens, Benjamin Bastida Virgili, Tim Flohrer

Astrophysical Journal Supplement Series **2021**

https://arxiv.org/pdf/2103.08059.pdf

The solar radio flux at F10.7 cm and F30 cm is required by most models characterizing the state of the Earth's upper atmosphere, such as the thermosphere and ionosphere to specify satellite orbits, re-entry services, collision avoidance maneuvers and modeling of space debris evolution. We develop a method called RESONANCE ("Radio Emissions from the Sun: ONline ANalytical Computer-aided Estimator") for the prediction of the 13-month smoothed monthly mean F10.7 and F30 indices 1-24 months ahead. The prediction algorithm includes three steps. First, we apply a 13-month optimized running mean technique to effectively reduce the noise in the radio flux data. Second, we provide initial predictions of the F10.7 and F30 indices using the McNish-Lincoln method. Finally, we improve these initial predictions by developing an adaptive Kalman filter with the error statistics identification. The root-mean-square-error of predictions with lead times from 1 to 24 months is 5-27 sfu for the F10.7 and 3-16 sfu for F30 index, which statistically outperforms current algorithms in use. The proposed approach based on Kalman filter is universal and can be applied to improve the initial predictions of a process under study provided by any other forecasting method. Furthermore, we present a systematic evaluation of re-entry forecast as an application to test the performance of F10.7 predictions on past ESA re-entry campaigns for payloads, rocket bodies, and space debris that re-entered from June 2006 to June 2019. The test results demonstrate that the predictions obtained by RESONANCE in general also lead to improvements in the forecasts of re-entry epochs.

What if we had a magnetograph at Lagrangian L5?

Alexei A. **Pevtsov**, Luca Bertello, Peter MacNeice, Gordon Petrie

Space Weather Volume 14, Issue 11, Version of Record online: 10 NOV **2016**

http://sci-hub.tw/10.1002/2016SW001471

Synoptic Carrington charts of magnetic field are routinely used as an input for modelings of solar wind and other aspects of space weather forecast. However, these maps are constructed using only the observations from the solar hemisphere facing Earth. The evolution of magnetic flux on the "farside" of the Sun, which may affect the topology of coronal field in the "nearside," is largely ignored. It is commonly accepted that placing a magnetograph in Lagrangian L5 point would improve the space weather forecast. However, the quantitative estimates of anticipated improvements have been lacking. We use longitudinal magnetograms from the Synoptic Optical Long-term Investigations of the Sun (SOLIS) to investigate how adding data from L5 point would affect the outcome of two major models used in space weather forecast.

Space weather research and forecast in USA **Review**

Alexei A. **Pevtsov**

Proceedings of XX annual Conference on Solar and Solar-Terrestrial Physics held at the Central (Pulkovo) Astronomical Observatory, 10-14 Oct. 2016. **2016 File**

https://arxiv.org/ftp/arxiv/papers/1611/1611.02652.pdf

In the United States, scientific research in space weather is funded by several Government Agencies including the National Science Foundation (NSF) and the National Aeronautics and Space Agency (NASA). For commercial purposes, space weather forecast is made by the Space Weather Prediction Center (SWPC) of the National Oceanic and Atmospheric Administration (NOAA). Observations come from the network of groundbased observatories funded via various sources, as well as from the instruments on spacecraft. Numerical models used in forecast are developed in the framework of individual research projects. Later, the most promising models are selected for additional testing at SWPC. In order to increase the application of models in research and education, NASA in collaboration with other agencies created Community Coordinated Modeling Center (CCMC). In mid-1990, US scientific community presented compelling evidence for developing the National Program on Space Weather, and in 1995, such program has been formally created. In 2015, the National Council on Science and Technology issued two documents: the National Space Weather Strategy [1] and the Action Plan [2]. In the near future, these two documents will define the development of Space Weather research and forecasting activity in USA. Both documents emphasize the need for close international collaboration in area of space weather.

[1] The National Space Weather Strategy, 2015, www.whitehouse.gov/sites/default/files/microsites/ostp/final_nationalspaceweatherstrategy_20151028.pdf

[2] The National Space Weather Action Plan, 2015, www.whitehouse.gov/sites/default/files/microsites/ostp/final_nationalspaceweatheractionplan_20151028.pdf

[3] The U.K. "National risk register for civil emergencies" (2015 edition), www.gov.uk/government/publications/national-risk-register-for-civil-emergencies-2015-edition

[4] Knipp, D. J. et al, 2016, The May 1967 great storm and radio disruption event: Extreme space weather and extraordinary responses, Space Weather, DOI: 10.1002/2016SW001423

[5] International Space Environment Service (ISES), www.spaceweather.org

Solar Physics Research in the Russian Subcontinent - Current Status and Future

A.A. **Pevtsov**, Yu. A. Nagovitsyn, A.G. Tlatov, M.L. Demidov

Asian Journal of Physics **2016**

http://arxiv.org/pdf/1606.01331v1.pdf

Modern research in solar physics in Russia is a multifaceted endeavor, which includes multi-wavelength observations from the ground- and space-based instruments, extensive theoretical and numerical modeling studies, new instrument development, and cross-disciplinary and international research. The research is conducted at the research organizations under the auspices of the Russian Academy of Sciences and to a lesser extent, by the research groups at Universities. Here, we review the history of solar physics research in Russia, and provide an update on recent developments.

The Need for Synoptic Solar Observations from the Ground

Pevtsov, A. A.

Ground-based Solar Observations in the Space Instrumentation Era

ASP Conference Series, Vol. 504, p. 71 **2016**

http://aspbooks.org/publications/504/071.pdf

Synoptic observations are indispensable in studies of long-term effects pertinent to variation in solar radiative output, space weather and space climate, as well as for understanding the physics of global processes taking place on our nearest star. Synoptic data also allow putting the Sun in the context of stellar evolution. Historically, the main-stay of such observations has been groundbased although the improving longevity of space-borne instruments puts some space missions into the category of synoptic facilities. Space- and groundbased (synoptic) observations are complementary to each other; neither is inferior or superior to the other. Groundbased facilities can have a long-term (50 years+) operations horizon, and in comparison with their spacebased counterparts, they are less expensive to operate and have fewer restrictions on international collaboration and data access. The instruments can be serviced, upgraded, and cross-calibrated to ensure the continuity and uniformity of long-term data series. New measurements could be added in response to changes in understanding the solar phenomena. Some drawbacks such as day-night cycle and the variable atmospheric seeing can be mitigated e.g., by creating global networks and by employing adaptive optics. Furthermore, the groundbased synoptic observations can serve as a backbone and a back-up to spacebased observations. Here I review some existing groundbased synoptic facilities, describe plans for future networks, and outline the current efforts in strengthening the international collaboration in synoptic solar observations from the ground.

The Great Québec Blackout 1989

DR.TONY **PHILLIPS**

March **2021**

https://spaceweatherarchive.com/2021/03/12/the-great-quebec-blackout/

FLARECAST: an I4.0 technology for space weather using satellite data

Michele **Piana**, Anna Maria Massone, Federico Benvenuto, Cristina Campi

IEEE Italy Session - 4th International Forum on Research and Technologies for Society and Industry **2018**

https://arxiv.org/ftp/arxiv/papers/1806/1806.08560.pdf

'Flare Likelihood and Region Eruption Forecasting (FLARECAST)' is a Horizon 2020 project, which realized a technological platform for machine learning algorithms, with the objective of providing the space weather community with a prediction service for solar flares. This paper describes the FLARECAST service and shows how the methods implemented in the platform allow both flare prediction and a quantitative assessment of how the information contained in the space data utilized in the analysis may impact the forecasting process.

North Europe power transmission system vulnerability during extreme space weather

Roberta **Piccinelli** and Elisabeth Krausmann*

J. Space Weather Space Clim. **2018**, 8, A03

https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc160049.pdf

Space weather driven by solar activity can induce geomagnetic disturbances at the Earth's surface that can affect power transmission systems. Variations in the geomagnetic field result in geomagnetically induced currents that can enter the system through its grounding connections, saturate transformers and lead to system instability and possibly collapse. This study analyzes the impact of extreme space weather on the northern part of the European power transmission grid for different transformer designs to understand its vulnerability in case of an extreme event. The behavior of the system was analyzed in its operational mode during a severe geomagnetic storm, and mitigation measures, like line compensation, were also considered. These measures change the topology of the system, thus varying the path of geomagnetically induced currents and inducing a local imbalance in the voltage stability superimposed on the grid operational flow. Our analysis shows that the North European power transmission system is fairly robust against extreme space weather events. When considering transformers more vulnerable to geomagnetic storms, only few episodes of instability were found in correspondence with an existing voltage instability due to the underlying system load. The presence of mitigation measures limited the areas of the network in which bus voltage instabilities arise with respect to the system in which mitigation measures are absent.

Geoelectric field evaluation during the September, 2017 Geomagnetic Storm: MA.I.GIC. model

M. **Piersanti** , S. Di Matteo , B.A. Carter , J. Currie , G. D'Angelo

Space Weather Volume17, Issue8 Pages 1241-1256 **2019**

sci-hub.se/10.1029/2019SW002202

The space environment near Earth is constantly subjected to changes in the solar wind flow generated at the Sun. Examples of this variability are the occurrence of powerful solar disturbances, such as coronal mass ejections (CMEs). The impact of CMEs on the Earth's magnetosphere perturbs the geomagnetic field causing the occurrence of geomagnetic storms. Such extremely variable geomagnetic fields trigger geomagnetic effects measurable not only in the geospace but also in the ionosphere, upper atmosphere, and on the ground. For example, during extreme events, rapidly changing geomagnetic fields generate intense geomagnetically induced currents (GICs). In recent years, GIC impact on the power networks at middle and low latitudes has attracted attention due to the expansion of large-scale power networks into these regions. This paper presents a new model, called MA.I.GIC. (Magnetosphere - Ionosphere - Ground Induced Current), to derive the geoelectric field used to determine the magnitude of GICs. In addition, we discuss the results of the MA.I.GIC. model applied to the September 2017 Geomagnetic Storm with particular focus on the two sudden impulses occurring on **September 6 and 7, 2017**, and the two main phases on **September 7 and 8, 2017**.

Theoretical basis for operational ensemble forecasting of coronal mass ejections

V. J. **Pizzo**, C. de Koning, M. Cash, G. Millward, D. A. Biesecker, L. Puga, M. Codrescu and D. Odstrcil

Space Weather v.13, No. 10 (pages 676–697) **2015** DOI: 10.1002/2015SW001221

We lay out the theoretical underpinnings for the application of the Wang-Sheeley-Arge-Enlil modeling system to ensemble forecasting of coronal mass ejections (CMEs) in an operational environment. In such models, there is no magnetic cloud component, so our results pertain only to CME front properties, such as transit time to Earth. Within this framework, we find no evidence that the propagation is chaotic, and therefore, CME forecasting calls for different tactics than employed for terrestrial weather or hurricane forecasting. We explore a broad range of CME cone inputs and ambient states to flesh out differing CME evolutionary behavior in the various dynamical domains (e.g., large, fast CMEs launched into a slow ambient, and the converse; plus numerous permutations in between). CME propagation in both uniform and highly structured ambient flows is considered to assess how much the solar wind background affects the CME front properties at 1 AU. Graphical and analytic tools pertinent to an ensemble approach are developed to enable uncertainties in forecasting CME impact at Earth to be realistically estimated. We discuss how uncertainties in CME pointing relative to the Sun-Earth line affects the reliability of a forecast and how glancing blows become an issue for CME off-points greater than about the half width of the estimated input CME. While the basic results appear consistent with established impressions of CME behavior, the next step is to use existing records of well-observed CMEs at both Sun and Earth to verify that real events appear to follow the systematic tendencies presented in this study.

Wang-Sheeley-Arge–Enlil Cone Model Transitions to Operations,

Pizzo, V., G. Millward, A. Parsons, D. Biesecker, S. Hill, and D. Odstrcil
(**2011**), Space Weather, 9, S03004, doi:10.1029/2011SW000663.; **File**

The National Weather Service's (NWS) Space Weather Prediction Center (SWPC) is transitioning the first large-scale, physics-based space weather prediction model into operations on the NWS National Centers for Environmental Prediction (NCEP) supercomputing system (see also C. Schultz, Space weather model moves into prime time, Space Weather, 9, S03005, doi:10.1029/2011SW000669, 2011). The model is intended to provide 1- to 4-day advance warning of geomagnetic storms from quasi-recurrent solar wind structures and Earth-directed coronal mass ejections (CMEs). A team has been put together at SWPC to bring an advanced numerical model—developed with broad participation of the research community—into operational status. The modeling system consists of two main parts: (1) a semiempirical near-Sun module (Wang-Sheeley-Arge (WSA)) that approximates the outflow at the base of the solar wind; and (2) a sophisticated three-dimensional magnetohydrodynamic numerical model (Enlil) that simulates the resulting flow evolution out to Earth. The former module is driven by observations of the solar surface magnetic field accumulated over a solar rotation and composited into a synoptic map; this input is used to drive a parameterized model of the near-Sun expansion of the solar corona, which provides input for the interplanetary module to compute the quasi-steady (ambient) solar wind outflow. Finally, when an Earth-directed CME is detected in coronagraph images from NASA spacecraft, these images are used to characterize the basic properties of the CME, including speed, direction, and size. This input "cone" representation is injected into the preexisting ambient flow, and the subsequent transient evolution forms the basis for the prediction of the CME's arrival time at Earth, its intensity, and its duration (Figure 1).

Current state and perspectives of Space Weather science in Italy

Christina **Plainaki1**,*, Marco Antonucci2 , Alessandro Bemporad3 , …
J. Space Weather Space Clim. **2020**, 10, 6
https://www.swsc-journal.org/articles/swsc/pdf/2020/01/swsc190014.pdf
– Italian teams have been involved many times in Space Weather observational campaigns from space and from the ground, contributing in the advancing of our knowledge on the properties and evolution of the related phenomena. Numerous Space Weather forecasting and now-casting modeling efforts have resulted in a remarkable add-on to the overall progress in the field, at both national and international level. The Italian Space Agency has participated several times in space missions with science objectives related to Space Weather; indeed, an important field for the Italian scientific and industrial communities interested in Heliophysics and Space Weather, is the development of new instrumentation for future space missions. In this paper, we present a brief state-of-the-art in Space Weather science in Italy and we discuss some ideas on a long-term plan for the support of future scientific research in the related disciplines. In the context of the current roadmap, the Italian Space Agency aims to assess the possibility to develop a national scientific Space Weather data centre to encourage synergies between different science teams with interest in the field and to motivate innovation and new mission concept development. Alongside with the proposed recommendations, we also discuss how the Italian expertise could complement international efforts in a wider international Space Weather context.

Planetary space weather: scientific aspects and future perspectives   Topical **Review**

Christina **Plainaki**1,2*, Jean Lilensten3, Aikaterini Radioti4, Maria Andriopoulou5,Anna Milillo1, Tom A. Nordheim6, Iannis Dandouras7, Athena Coustenis8, Davide Grassi1, Valeria Mangano1, Stefano Massetti1, Stefano Orsini1 and Alice Lucchetti
J. Space Weather Space Clim., 6, A31 (**2016**)   Open Access

In this paper, we review the scientific aspects of planetary space weather at different regions of our Solar System, performing a comparative planetology analysis that includes a direct reference to the circum-terrestrial case. Through an interdisciplinary analysis of existing results based both on observational data and theoretical models, we review the nature of the interactions between the environment of a Solar System body other than the Earth and the impinging plasma/radiation, and we offer some considerations related to the planning of future space observations. We highlight the importance of such comparative studies for data interpretations in the context of future space missions (e.g. ESA JUICE; ESA/JAXA BEPI COLOMBO). Moreover, we discuss how the study of planetary space weather can provide feedback for better understanding the traditional circum-terrestrial space weather. Finally, a strategy for future global investigations related to this thematic is proposed.

Geomagnetic storm forecasting service StormFocus: 5 years online

Tatiana **Podladchikova**, Anatoly Petrukovich and Yuri Yermolaev

J. Space Weather Space Clim. **2018**, 8, A22

https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc170027.pdf

Forecasting geomagnetic storms is highly important for many space weather applications. In this study, we review performance of the geomagnetic storm forecasting service StormFocus during 2011–2016. The service was implemented in 2011 at SpaceWeather.Ru and predicts the expected strength of geomagnetic storms as measured by Dst index several hours ahead. The forecast is based on L1 solar wind and IMF measurements and is updated every hour. The solar maximum of cycle 24 is weak, so most of the statistics are on rather moderate storms. We verify quality of selection criteria, as well as reliability of real-time input data in comparison with the final values, available in archives. In real-time operation 87% of storms were correctly predicted while the reanalysis running on final OMNI data predicts successfully 97% of storms. Thus the main reasons for prediction errors are discrepancies between real-time and final data (Dst, solar wind and IMF) due to processing errors, specifics of datasets. **6 August 2011, 10-11 Sept 2011, 1-2 Nov 2011, 27-28 Aug 2015**

The Virtual Space Weather Modelling Centre

Stefaan **Poedts**1,9*, Andrey Kochanov1, Andrea Lani1, Camilla Scolini1,2, Christine Verbeke1 et al.

J. Space Weather Space Clim. **2020**, **10**, 14

https://www.swsc-journal.org/articles/swsc/pdf/2020/01/swsc190070.pdf

Aims. Our goal is to develop and provide an open end-to-end (Sun to Earth) space weather modeling system, enabling to combine ("couple") various space weather models in an integrated tool, with the models located either locally or geographically distributed, so as to better understand the challenges in creating such an integrated environment.

Methods. The physics-based models are installed on different compute clusters and can be run interactively and remotely and that can be coupled over the internet, using open source "high-level architecture" software, to make complex modeling chains involving models from the Sun to the Earth. Visualization tools have been integrated as "models" that can be coupled to any other integrated model with compatible output.

Results. The first operational version of the VSWMC is accessible via the SWE Portal and demonstrates its end-to-end simulation capability. Users interact via the front-end GUI and can interactively run complex coupled simulation models and view and retrieve the output, including standard visualizations, via the GUI. Hence, the VSWMC provides the capability to validate and compare model outputs.

A Prospective New Diagnostic Technique for Distinguishing Eruptive and Non-Eruptive Active Regions

P. **Pagano**, D.H. Mackay, S.L. Yardley

ApJ **883** 112 **2019**

https://arxiv.org/pdf/1908.09223.pdf

https://doi.org/10.3847/1538-4357/ab3e42

Active regions are the source of the majority of magnetic flux rope ejections that become Coronal Mass Ejections (CMEs). To identify in advance which active regions will produce an ejection is key for both space weather prediction tools and future science missions such as Solar Orbiter. The aim of this study is to develop a new technique to identify which active regions are more likely to generate magnetic flux rope ejections. The new technique will aim to: (i) produce timely space weather warnings and (ii) open the way to a qualified selection of observational targets for space-borne instruments. We use a data-driven Non-linear Force-Free Field (NLFFF) model to describe the 3D evolution of the magnetic field of a set of active regions. We determine a metric to distinguish eruptive from non-eruptive active regions based on the Lorentz force. Furthermore, using a subset of the observed magnetograms, we run a series of simulations to test whether the time evolution of the metric can be predicted. The identified metric successfully differentiates active regions observed to produce eruptions from the non-eruptive ones in our data sample. A meaningful prediction of the metric can be made between 6 to 16 hours in advance. This initial study presents an interesting first step in the prediction of CME onset using only LOS magnetogram observations combined with NLFFF modelling. Future studies will address how to generalise the

model such that it can be used in a more operational sense and for a variety of simulation approaches. **2012.08.29-09.02**
Table 1. Properties of the active regions analysed in this study (2012-2015)

Interplanetary radio type II and type IV bursts as indicators of propagating solar transients

Silja **Pohjolainen**, Nasrin Talebpour Sheshvan

Proceedings of 2nd URSI AT-RASC Meeting in Gran Canaria, 28 May - 1 June 2018 **2018**

https://arxiv.org/ftp/arxiv/papers/1806/1806.05065.pdf

Recent studies of interplanetary radio type II bursts and their source locations are reviewed. As these bursts are due to propagating shock waves, driven by coronal mass ejections, they can be followed to near-Earth distances and can be used to predict the arrival times of geo-effective disturbances. Radio type IV bursts, on the other hand, are usually due to moving magnetic structures in the low corona and trapped particles form at least part of the emission. The observed directivity of type IV emission may also be used for space weather purposes. **22 September 2011**

EUHFORIA: European heliospheric forecasting information asset

Jens **Pomoell**1* and S. Poedts2

J. Space Weather Space Clim. **2018**, 8, A35

https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc170062.pdf

The implementation and first results of the new space weather forecasting-targeted inner heliosphere model "European heliospheric forecasting information asset" (EUHFORIA) are presented. EUHFORIA consists of two major components: a coronal model and a heliosphere model including coronal mass ejections. The coronal model provides data-driven solar wind plasma parameters at 0.1 AU by constructing a magnetic field model of the coronal large-scale magnetic field and employing empirical relations to determine the plasma state such as the solar wind speed and mass density. These are then used as boundary conditions to drive a three-dimensional time-dependent magnetohydrodynamics model of the inner heliosphere up to 2 AU. CMEs are injected into the ambient solar wind modeled using the cone model, with their parameters obtained from fits to imaging observations. In addition to detailing the modeling methodology, an initial validation run is presented. The results feature a highly dynamic heliosphere that the model is able to capture in good agreement with in situ observations. Finally, future horizons for the model are outlined.

Focused Space Weather Strategy for Securing Earth, and Human Exploration of the Moon and Mars

A. **Posner**, N. Arge, K. Cho, B. Heber, F. Effenberger, T. Y. Chen, S. Krucker, P. Kühl, O. Malandraki, Y.-D. Park, A. Pulkkinen, N. Raouafi, S. K. Solanki, O. C. StCyr, R. D. Strauss

Heliophysics 2050 White Paper **2023**

https://arxiv.org/ftp/arxiv/papers/2301/2301.04136.pdf

This white paper recognizes gaps in observations that will, when addressed, much improve solar radiation hazard and geomagnetic storm forecasting. Radiation forecasting depends on observations of the entire "Solar Radiation Hemisphere" that we will define. Mars exploration needs strategic placement of radiation-relevant observations. We also suggest an orbital solution that will improve geomagnetic storm forecasting through improved in situ and solar/heliospheric remote sensing.

The main pillar: Assessment of space weather observational asset performance supporting nowcasting, forecasting, and research to operations

A. **Posner**, M. Hesse and O. C. St. Cyr

Space Weather, Volume 12, Issue 4, pages 257–276, April **2014**

Space weather forecasting critically depends upon availability of timely and reliable observational data. It is therefore particularly important to understand how existing and newly planned observational assets perform during periods of severe space weather. Extreme space weather creates challenging conditions under which instrumentation and spacecraft may be impeded or in which parameters reach values that are outside the nominal observational range. This paper analyzes existing and upcoming observational capabilities for forecasting, and discusses how the findings may impact space weather research and its transition to operations. A single limitation to the assessment is lack of information provided to us on radiation monitor performance, which caused us not to fully assess (i.e., not assess short term) radiation storm forecasting. The assessment finds that at least two widely spaced coronagraphs including L4 would provide reliability for Earth-bound CMEs. Furthermore, all magnetic field measurements assessed fully meet requirements. However, with current or even with near term new assets in place, in the worst-case scenario there could be a near-complete lack of key near-real-time solar wind plasma data of severe disturbances heading toward and impacting Earth's magnetosphere. Models that attempt to simulate the effects of these disturbances in near real time or with archival data require solar wind plasma observations as input. Moreover, the study finds that near-future observational assets will be less capable of advancing the understanding of extreme geomagnetic disturbances at Earth, which might make the resulting space weather models unsuitable for transition to operations.

A New Trend in Forecasting Solar Radiation Hazards

Posner, Arik; Guetersloh, Stephen; Heber, Bernd; Rother, Oliver

Space Weather, Vol. 7, No. 5, S05001, **2009**

http://www.agu.org/pubs/crossref/2009/2009SW000476.shtml

Several international space agencies plan to send astronauts beyond low-Earth orbit in the coming decades to explore the Moon or other nearby planetary objects. Humans leaving the Earth's magnetosphere enter the solar wind, potentially exposing themselves to prompt solar energetic particle (SEP) events, which are sudden outbursts of energetic particle radiation of solar origin. Accurate warning of SEP radiation hazards through an operational forecasting system, even if only an hour in advance, allows contingency plans to be set in motion rapidly. The potential for expanding mission operations capabilities with such warnings has been acknowledged by the NASA Space Radiation Analysis Group at Johnson Space Center. As NASA gears up to send astronauts to the Moon and Mars, projected radiation doses on such long-term missions approach current career limits, so avoiding sudden exposure from SEP events becomes crucial.

http://www.agu.org/journals/sw/swa/free/newarticle/?id=2009SW000476&page=1#citation

See Labrenz et al. (**2016**) Near realtime forecasting of MeV protons on the basis of sub relativistic electrons EGU General Assembly 2016, held 17-22 April, 2016 in Vienna Austria, p.8076

Up to 1-hour forecasting of radiation hazards from solar energetic ion events with relativistic electrons,

Posner, A.,

Space Weather, Vol. 5, No. 5, S05001, doi:10.1029/2006SW000268, **2007**.

The sudden and prompt occurrence of solar energetic particle events poses a hazard to manned space activities and interferes with robotic space science missions. This study demonstrates the possibility of short-term forecasting of the appearance and intensity of solar ion events by means of relativistic, near–light speed electrons. A list of the most severe proton events measured by GOES 8 in the years 1996–2002 serves as a basis to derive the fundamentals of the forecasting method with statistical and superposed epoch techniques. The Comprehensive Suprathermal and Energetic Particle Analyzer (COSTEP) on SOHO provides relativistic electron and <50 MeV proton observations at 1 AU. With a subset of solar particle events (SPEs) where the location of the associated flare on the Sun has been determined, we find that (1) relativistic electrons always arrive at 1 AU ahead of nonrelativistic SPEs allowing their forecasting; (2) the intensity increase of both, electrons and protons alike, depends on the magnetic connection, i.e., the magnetic longitude difference between the observer and the flare; and (3) as coming from one source under near-identical propagation conditions, significant correlations exist that show that the early electron intensity and increase can be utilized as a matrix to forecast the upcoming proton intensity. The study demonstrates one initial empirical forecasting technique with electron and proton observations in 2003.

The Space Weather Modeling Framework goes open access,

Pulkkinen, T., T. I. Gombosi, A. J. Ridley, G. Toth, and S. Zou

(**2021**),Eos, 102,

https://doi.org/10.1029/2021EO158300.

A versatile suite of computational models, already used to forecast magnetic storms and potential power grid and telecommunications disruptions, is preparing to welcome a larger group of users.

Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow (PROSWIFT)

Geomagnetically induced currents: Science, engineering, and applications readiness Review

Pulkkinen A., E. Bernabeu, A. Thomson, A. Viljanen, R. Pirjola, D. Boteler, J. Eichner, P. J. Cilliers, D. Welling, N. P. Savani, et al

Space Weather Volume 15, Issue 7 July **2017** Pages 828–856

http://sci-hub.cc/10.1002/2016SW001501

https://doi.org/10.1002/2016SW001501

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2016SW001501

This paper is the primary deliverable of the very first NASA Living With a Star Institute Working Group, Geomagnetically Induced Currents (GIC) Working Group. The paper provides a broad overview of the current status and future challenges pertaining to the science, engineering, and applications of the GIC problem. Science is understood here as the basic space and Earth sciences research that allows improved understanding and physics-based modeling of the physical processes behind GIC. Engineering, in turn, is understood here as the “impact” aspect of GIC. Applications are understood as the models, tools, and activities that can provide actionable information to entities such as power systems operators for mitigating the effects of GIC and government agencies for managing any potential consequences from GIC impact to critical infrastructure. Applications can be considered the ultimate goal of our GIC work. In assessing the status of the field, we quantify the readiness of various applications in the mitigation context. We use the Applications Readiness Level (ARL) concept to carry out the quantification.

Geomagnetically Induced Currents Modeling and Forecasting
Antti **Pulkkinen**
Space Weather Volume 13, Issue 11 November **2015** Pages 734–736
SWQuarterly Vol. 13, Issue 1, **2016**
http://onlinelibrary.wiley.com/doi/10.1002/2015SW001316/pdf
http://onlinelibrary.wiley.com/doi/10.1002/SWQv13i001/epdf

Space Weather: Terrestrial Perspective
Tuija **Pulkkinen**
Living Rev. Solar Phys., 4, (**2007**), 1, **File**
http://www.livingreviews.org/lrsp-2007-1
Space weather effects arise from the dynamic conditions in the Earth’s space environment driven by processes on the Sun. While some effects are influenced neither by the properties of nor the processes within the Earth’s magnetosphere, others are critically dependent on the interaction of the impinging solar wind with the terrestrial magnetic field and plasma environment. As the utilization of space has become part of our everyday lives, and as our lives have become increasingly dependent on technological systems vulnerable to space weather influences, understanding and predicting hazards posed by the active solar events has grown in importance. This review introduces key dynamic processes within the magnetosphere and discusses their relationship to space weather hazards.

Chapter 24 - Recent Geoeffective Space Weather Events and Technological System Impacts **Review**
Robert J. **Redmon***William F.Denig*Paul T.M.Loto'aniu*†DominicFuller-Rowell
In: Extreme Events in Geospace Origins, Predictability, and Consequences **2018**, Pages 587-609
http://sci-hub.tw/10.1016/B978-0-12-812700-1.00024-8
On **February 27, 2014**, the U.S. Wide Area Augmentation System (WAAS) navigation service covering eastern Alaska and the northeastern continental United States, and the similar European Geostationary Navigation Overlay Service (EGNOS) covering northern Europe were both degraded due to a strong ionospheric storm that occurred during a relatively modest geomagnetic storm (Dstmin ≈ − 94 nT). Similarly, on **March 17, 2015**, the St. Patrick's Day strong geomagnetic storm (Dstmin ≈ − 223 nT) resulted in the most intense storm of the solar cycle to date with mid-latitude auroral sightings, and intense ionospheric irregularities. Finally, on **June 22, 2015**, a strong geomagnetic storm (Dstmin ≈ − 204 nT) commenced following the impact of 3 coronal mass ejections (CMEs). All three events resulted in impacts to WAAS and EGNOS services over important coverage areas. This chapter focuses on operational data products available from the U.S. National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI) for assessing the state of the space environment. We describe observations of the solar disk and the geospace radiation environment, and predictions of the energy input into the auroral region, and the resulting ionosphere response. We demonstrate that operational data help to follow the chain of events from Sun-to-Earth leading to disruptive space weather effects to technological systems such as spacecraft operations, radio communication, and aviation products. This chapter culminates in a discussion of how these storms impacted U.S. and European aviation systems. We emphasize: (i) significant degradation in performance of technological systems has been observed for three geomagnetic storms with Dstmin ≲ − 100 nT, and (ii) if historically extreme events (e.g., a Carrington-like event) occurred today they, would lead to much more adverse effects for the considered systems.

September 2017’s Geoeffective Space Weather and Impacts to Caribbean Radio Communications during Hurricane Response
Robert **Redmon** , Daniel Seaton, Robert Steenburgh, Jing He, Juan Rodriguez
EARTH AND SPACE SCIENCE OPEN ARCHIVE (ESSOAR) **2018**
(ESSOAR https://news.agu.org/press-release/essoar-preprint-server-open-submissions/)

Space Weather Journal special collection: “Space Weather Events of 4–10 September 2017” **2018**
https://www.essoar.org/doi/pdf/10.1002/essoar.a530e85443c2d357.102532a29f074aec.2
Between **4 and 10 September 2017**, multiple solar eruptions occurred from active region AR12673. NOAA and NASA’s well-instrumented spacecraft observed the evolution of these geoeffective events from their solar origins, through the interplanetary medium, to their geospace impacts. The 6 September X9.3 flare was the largest to date for the nearly concluded solar cycle 24 and, in fact, the brightest recorded since an X17 flare in September 2005, which occurred during the declining phase of solar cycle 23. Rapid ionization of the sunlit upper atmosphere occurred, disrupting high frequency communications in the Caribbean region while emergency managers were scrambling to provide critical recovery services caused by the region’s devastating hurricanes. The 10 September west limb eruption resulted in the first solar energetic particle event since 2012 with sufficient flux and energy to yield a ground level enhancement. Spacecraft at L1, including DSCOVR, sampled the associated interplanetary coronal mass ejections minutes before their collision with Earth’s magnetosphere. Strong compression and erosion of the dayside magnetosphere occurred, placing geosynchronous satellites in the magnetosheath. Subsequent geomagnetic storms produced magnificent auroral displays and elevated hazards to power systems. Through the lens of NOAA’s space weather R-S-G storm scales, this event period increased hazards for systems susceptible to elevated “radio blackout” (R3-strong), “solar radiation storm” (S3-strong), and “geomagnetic storm” (G4-severe) conditions. The purpose of this paper is to provide an overview of the September 2017 space weather event, and a summary of its consequences, including forecaster, post event analyst and communication operator perspectives.

Forecasting the Remaining Duration of an Ongoing Solar Flare

Jeffrey W. **Reep**, Will T. Barnes
Space Weather **Volume19, Issue10** e2021SW002754 **2021**
https://arxiv.org/pdf/2103.03957.pdf
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021SW002754
https://doi.org/10.1029/2021SW002754
The solar X-ray irradiance is significantly heightened during the course of a solar flare, which can cause radio blackouts due to ionization of the atoms in the ionosphere. As the duration of a solar flare is not related to the size of that flare, it is not directly clear how long those blackouts can persist. Using a random forest regression model trained on data taken from X-ray light curves, we have developed a direct forecasting method that predicts how long the event will remain above background levels. We test this on a large collection of flares observed with GOES-15, and show that it generally outperforms simple linear regression. This forecast is computationally light enough to be performed in real time, allowing for the prediction to be made during the course of a flare. **2012-09-01, 2012-10-20, 2013-11-05-06, 2014-09-10, 2015-11-23, 2016-03-12**

Defining Radiation Belt Enhancement Events Based on Probability Distributions

Geoffrey D. **Reeves**, Elizabeth M. Vandegriff, Jonathan T. Niehof, Steven K. Morley, Gregory S. Cunningham, Michael G. Henderson, Brian A. Larsen,
Space Weather **Volume18, Issue8** e2020SW002528 **2020**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020SW002528
We present a methodology to define moderate, strong, and intense space weather events based on probability distributions. We have illustrated this methodology using a long-duration, uniform data set of 1.8–3.5 MeV electron fluxes from multiple LANL geosynchronous satellite instruments, but a strength of this methodology is that it can be applied uniformly to heterogeneous data sets. It allows quantitative comparison of data sets with different energies, units, orbits, and so forth. The methodology identifies a range of times, “events,” using variable flux thresholds to determine average event occurrence in arbitrary 11-year intervals (“cycles”). We define moderate, strong, and intense events as those that occur 100, 10, and 1 time per cycle and identify the flux thresholds that produce those occurrence frequencies. The methodology does not depend on any ancillary data set (e.g., solar wind or geomagnetic conditions). We show event probabilities using GOES > 2 MeV fluxes and compare them against event probabilities using LANL 1.8–3.5 MeV fluxes. We present some examples of how the methodology picks out moderate, strong, and intense events and how those events are distributed in time: 1989 through 2018, which includes the declining phases of solar cycles 22, 23, and 24. We also provide an illustrative comparison of moderate and strong events identified in the geosynchronous data with Van Allen Probes observations across all L-shells. We also provide a catalog of start and stop times of moderate, strong, and intense events that can be used for future studies.
https://zenodo.org/record/3764205
Table 2. A Catalog of Event Start and Stop Dates for Moderate Events Which Occur, on Average, 100 Times in 11 Years
Table 3. A Catalog of Event Start and Stop Dates for Strong Events Which Occur, on Average, 10 Times in 11 Years
Table 4. A Catalog of Event Start and Stop Dates for Intense Events Which Occur, on Average, Once in 11 Years

Forecasting space weather: Can new econometric methods improve accuracy?

Gordon **Reikard**

Advances in Space Research, Volume 47, Issue 12, 15 June **2011**, Pages 2073-2080

Space weather forecasts are currently used in areas ranging from navigation and communication to electric power system operations. The relevant forecast horizons can range from as little as 24 h to several days. This paper analyzes the predictability of two major space weather measures using new time series methods, many of them derived from econometrics. The data sets are the Ap geomagnetic index and the solar radio flux at 10.7 cm. The methods tested include nonlinear regressions, neural networks, frequency domain algorithms, GARCH models (which utilize the residual variance), state transition models, and models that combine elements of several techniques. While combined models are complex, they can be programmed using modern statistical software. The data frequency is daily, and forecasting experiments are run over horizons ranging from 1 to 7 days. Two major conclusions stand out. First, the frequency domain method forecasts the Ap index more accurately than any time domain model, including both regressions and neural networks. This finding is very robust, and holds for all forecast horizons. Combining the frequency domain method with other techniques yields a further small improvement in accuracy. Second, the neural network forecasts the solar flux more accurately than any other method, although at short horizons (2 days or less) the regression and net yield similar results. The neural net does best when it includes measures of the long-term component in the data.

Verification of high-speed solar wind stream forecasts using operational solar wind models

Martin A. **Reiss**, Manuela Temmer, Astrid M. Veronig, Ljubomir Nikolic, Susanne Vennerstrom, Florian Schöngassner, Stefan J. Hofmeister

Space Weather Volume 14, Issue 7 July **2016** Pages 495–510

High-speed solar wind streams emanating from coronal holes are frequently impinging on the Earth's magnetosphere causing recurrent, medium-level geomagnetic storm activity. Modeling high-speed solar wind streams is thus an essential element of successful space weather forecasting. Here we evaluate high-speed stream forecasts made by the empirical solar wind forecast (ESWF) and the semiempirical Wang-Sheeley-Arge (WSA) model based on the in situ plasma measurements from the Advanced Composition Explorer (ACE) spacecraft for the years 2011 to 2014. While the ESWF makes use of an empirical relation between the coronal hole area observed in Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly (AIA) images and solar wind properties at the near-Earth environment, the WSA model establishes a link between properties of the open magnetic field lines extending from the photosphere to the corona and the background solar wind conditions. We found that both solar wind models are capable of predicting the large-scale features of the observed solar wind speed (root-mean-square error, RMSE ≈100 km/s) but tend to either overestimate (ESWF) or underestimate (WSA) the number of high-speed solar wind streams (threat score, TS ≈ 0.37). The predicted high-speed streams show typical uncertainties in the arrival time of about 1 day and uncertainties in the speed of about 100 km/s. General advantages and disadvantages of the investigated solar wind models are diagnosed and outlined.

Prediction of Solar Energetic Particle Event Peak Proton Intensity Using a Simple Algorithm Based on CME Speed and Direction and Observations of Associated Solar Phenomena

I. G. **Richardson** , M. L. Mays, B. J. Thompson

Space Weather **Volume16, Issue11** **2018** Pages 1862-1881

sci-hub.tw/10.1029/2018SW002032

We assess whether a formula obtained by Richardson et al. [2014] relating the peak intensity of 14-24 MeV protons in a solar energetic particle (SEP) event at 1 AU to the solar event location and the speed of the associated coronal mass ejection (CME), may be used in a scheme to predict the intensity of an SEP event at any location at this heliocentric distance. Starting with all 334 CMEs in the CCMC/SWRC DONKI database in October 2011 – July 2012, we use the CME speed and direction to predict the proton intensity at Earth and the two STEREO spacecraft using this formula. Since most (~85%) of these CMEs were not in fact associated with SEP events, many SEP events are predicted that are not actually observed. Such cases may be reduced by considering whether type II or type III radio emissions accompany the CMEs, or by selecting faster, wider CMEs. This method is also applied to predict the SEP intensities associated with ∼1100 CMEs observed by the SOHO LASCO coronagraphs during 1997–2006 in solar cycle 23. Various skill scores are calculated which assess different aspects of the skill of the SEP predictions. We conclude that the Richardson et al. [2014] formula has potential as a simple empirical SEP intensity prediction tool.

Chapter 5 - Statistics of Extreme Space Weather Events **Review**

Pete **Riley**

In: Extreme Events in Geospace

Origins, Predictability, and Consequences **Book**

Editor: Natalia **Buzulukova**, Elsevier, **2018**, 798 p. **File**
Pages 115-138
http://sci-hub.se/10.1016/B978-0-12-812700-1.00005-4
Extreme events, while rare, can have a disproportionately large effect on our technologically dependent society. In this chapter, we review statistical approaches for estimating how likely such events are. In particular, we focus on the disturbance storm time (Dst) index, finding that the likelihood of an extreme geomagnetic storm (Dst < −850 nT) occurring over the next decade is approximately 10%. Crucially, however, the 95% interval lies between 1% and 20%, a span of more than an order of magnitude, which, unfortunately, is disappointing from a policy-implementation perspective. We add to previous studies by estimating the probability of extreme events based on the auroral electrojet AE index, and extend our previous Dstwork to also include the Dst proxy parameters Dxt and Dcx, which extend significantly further back in time. Additionally, we extend our previous analysis of solar proton events using a more rigorous approach. Our results suggest that these events are on the scale of 100-year solar storms; however, the extent to which they will occur in the future depends on a basic assumption in the methodology: time stationarity. We conclude by discussing the implications of this work, and suggest how future studies may improve our understanding.

Extreme Space Weather Events: From Cradle to Grave **Review**
Pete **Riley**, Dan Baker, Ying D. Liu, Pekka Verronen, Howard Singer, Manuel Güdel
Space Science Reviews February **2018**, 214:21
https://link.springer.com/article/10.1007/s11214-017-0456-3
https://link.springer.com/content/pdf/10.1007%2Fs11214-017-0456-3.pdf
Extreme space weather events, while rare, can have a substantial impact on our technologically-dependent society. And, although such events have only occasionally been observed, through careful analysis of a wealth of space-based and ground-based observations, historical records, and extrapolations from more moderate events, we have developed a basic picture of the components required to produce them. Several key issues, however, remain unresolved. For example, what limits are imposed on the maximum size of such events? What are the likely societal consequences of a so-called "100-year" solar storm? In this review, we summarize our current scientific understanding about extreme space weather events as we follow several examples from the Sun, through the solar corona and inner heliosphere, across the magnetospheric boundary, into the ionosphere and atmosphere, into the Earth's lithosphere, and, finally, its impact on man-made structures and activities, such as spacecraft, GPS signals, radio communication, and the electric power grid. We describe preliminary attempts to provide probabilistic forecasts of extreme space weather phenomena, and we conclude by identifying several key areas that must be addressed if we are better able to understand, and, ultimately, predict extreme space weather events.

Extreme geomagnetic storms: Probabilistic forecasts and their uncertainties
Pete **Riley**, Jeffrey J. Love
Space Weather Volume 15, Issue 1 January **2017** Pages 53–64
http://sci-hub.si/10.1002/2016SW001470
Extreme space weather events are low-frequency, high-risk phenomena. Estimating their rates of occurrence, as well as their associated uncertainties, is difficult. In this study, we derive statistical estimates and uncertainties for the occurrence rate of an extreme geomagnetic storm on the scale of the Carrington event (or worse) occurring within the next decade. We model the distribution of events as either a power law or lognormal distribution and use (1) Kolmogorov-Smirnov statistic to estimate goodness of fit, (2) bootstrapping to quantify the uncertainty in the estimates, and (3) likelihood ratio tests to assess whether one distribution is preferred over another. Our best estimate for the probability of another extreme geomagnetic event comparable to the Carrington event occurring within the next 10 years is 10.3% 95% confidence interval (CI) [0.9,18.7] for a power law distribution but only 3.0% 95% CI [0.6,9.0] for a lognormal distribution. However, our results depend crucially on (1) how we define an extreme event, (2) the statistical model used to describe how the events are distributed in intensity, (3) the techniques used to infer the model parameters, and (4) the data and duration used for the analysis. We test a major assumption that the data represent time stationary processes and discuss the implications. If the current trends persist, suggesting that we are entering a period of lower activity, our forecasts may represent upper limits rather than best estimates.

On the probability of occurrence of extreme space weather events
Pete **Riley**
Space Weather, Volume 10, Issue 2, February **2012**
https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2011SW000734
By virtue of their rarity, extreme space weather events, such as the Carrington event of 1859, are difficult to study, their rates of occurrence are difficult to estimate, and prediction of a specific future event is virtually impossible. Additionally, events may be extreme relative to one parameter but normal relative to others. In this study, we analyze several measures of the severity of space weather events (flare intensity, coronal mass ejection speeds, Dst,

and >30 MeV proton fluences as inferred from nitrate records) to estimate the probability of occurrence of extreme events. By showing that the frequency of occurrence scales as an inverse power of the severity of the event, and assuming that this relationship holds at higher magnitudes, we are able to estimate the probability that an event larger than some criteria will occur within a certain interval of time in the future. For example, the probability of another Carrington event (based on Dst < −850 nT) occurring within the next decade is ∼12%. We also identify and address several limitations with this approach. In particular, we assume time stationarity, and thus, the effects of long-term space climate change are not considered. While this technique cannot be used to predict specific events, it may ultimately be useful for probabilistic forecasting.
A Space weather information service based upon remote and in-situ measurements of coronal mass ejections heading for Earth

A concept mission consisting of six spacecraft in a heliocentric orbit at 0.72 AU

Birgit **Ritter**1*, Arjan J. H. Meskers2, Oscar Miles3, Michael Rußwurm4, Stephen Scully5, Andrés Roldán6, Oliver Hartkorn7, Peter Jüstel8, Victor Réville9, Sorina Lupu10 and Alexis Ruffenach

J. Space Weather Space Clim., 5, A3 (**2015**)

http://www.swsc-journal.org/articles/swsc/pdf/2015/01/swsc140007.pdf

The Earth's magnetosphere is formed as a consequence of interaction between the planet's magnetic field and the solar wind, a continuous plasma stream from the Sun. A number of different solar wind phenomena have been studied over the past 40 years with the intention of understanding and forecasting solar behavior. One of these phenomena in particular, Earth-bound interplanetary coronal mass ejections (CMEs), can significantly disturb the Earth's magnetosphere for a short time and cause geomagnetic storms. This publication presents a mission concept consisting of six spacecraft that are equally spaced in a heliocentric orbit at 0.72 AU. These spacecraft will monitor the plasma properties, the magnetic field's orientation and magnitude, and the 3D-propagation trajectory of CMEs heading for Earth. The primary objective of this mission is to increase space weather forecasting time by means of a near real-time information service, that is based upon in-situ and remote measurements of the aforementioned CME properties. The obtained data can additionally be used for updating scientific models. This update is the mission's secondary objective. In-situ measurements are performed using a Solar Wind Analyzer instrumentation package and fluxgate magnetometers, while for remote measurements coronagraphs are employed. The proposed instruments originate from other space missions with the intention to reduce mission costs and to streamline the mission design process. Communication with the six identical spacecraft is realized via a deep space network consisting of six ground stations. They provide an information service that is in uninterrupted contact with the spacecraft, allowing for continuous space weather monitoring. A dedicated data processing center will handle all the data, and then forward the processed data to the SSA Space Weather Coordination Center which will, in turn, inform the general public through a space weather forecast. The data processing center will additionally archive the data for the scientific community. The proposed concept mission allows for major advances in space weather forecasting time and the scientific modeling of space weather.

Current Space Weather Forecasting **Review**

E.**Robbrecht**

ESPM Presentation, **2011, File**

Big flare forecasting; CMEs, Are halo CMEs special? geoeffectiveness of CMEs; CME travel times; Predicting "Bz"; CMEs can rotate

Хорошие ссылки

The SPASE Data Model: A Metadata Standard for Registering, Finding, Accessing, and Using Heliophysics Data Obtained From Observations and Modeling

D. Aaron **Roberts**, James Thieman, Vincent Génot, Todd King, Michel Gangloff, Chris Perry, Chiu Wiegand , Darren De Zeeuw, Shing F. Fung, Baptiste Cecconi, Sébastien Hess

Space Weather 16, 12, 1899-1911 **2018**

sci-hub.tw/10.1029/2018SW002038

The Space Physics Archive Search and Extract Consortium has developed and implemented the SPASE Data Model that provides a common language for registering a wide range of Heliophysics data and other products. The Data Model enables discovery and access tools such that any researcher can obtain data easily, thereby facilitating research, including on space weather. The Data Model includes descriptions of Simulation Models and Numerical Output, pioneered by the Integrated Medium for Planetary Exploration (IMPEx) group in Europe, and subsequently adopted by the Community Coordinated Modeling Center (CCMC). The SPASE group intends to register all relevant Heliophysics data resources, including space-, ground-, and model-based. Substantial progress has been made, especially for space-based observational data and associated observatories, instruments, and display data. Legacy product registrations and access go back more than 50 years. Real-time data will be included. The National Aeronautics and Space Administration (NASA) portion of the SPASE group has funding that assures continuity in the upkeep of the Data Model and aids with adding new products. Tools are being developed for making and editing data descriptions. Digital Object Identifiers (DOIs) for Data Products can now be included in the descriptions. The data access that SPASE facilitates is becoming more uniform, and work is progressing on Web Service access via a standard Application Programming Interface. The SPASE Data Model is stable; changes over the past 9 years were additions of terms and capabilities that are backward compatible. This paper provides a summary of the history, structure, use, and future of the SPASE Data Model.

Mission Specific Solar Radiation Environment Model (MSSREM): Peak Flux Model

Z. D. **Robinson** , J. H. Adams Jr. , J. H. Fisher , J. H. Nonnast , D. C. Terry

Space Weather **Volume18, Issue8** e2019SW002361 **2020**

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019SW002361

https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2019SW002361?casa_token=knatZXk6yzQAAAAA:EEaXKw2cyMDGm00jGpRp37kceJnEwZZh39KXiwmUmfMTOI_EtmCRKgGyh4mlN6lA5tGU7k2BAITE1tTx

Coronal mass ejections (CMEs) and solar flares can accelerate high fluxes of energetic particles. Depending on where this solar activity occurs on the sun, these outward moving particles can reach the Earth and enter the Earth's magnetosphere. They can also strike manmade objects in space. If the electronics in space are not protected from these energetic particles, they can cause the spacecraft to reboot, go into 'safe mode', have other anomalies, or cause catastrophic damage and loss of the mission. To protect the mission, the user can employ one or more mitigation strategies. The user may choose to add shielding, choose parts less prone to radiation effects and/or mitigate by design. Implementing any of these strategies adds cost to the mission so it is important to frame the design for the purpose of survival in a reference environment which is severe enough to provide the desired confidence of mission success, but not more. For this reason, models have been developed that construct a design reference environment tailored to a specific mission. In this paper, the Mission-Specific Solar Radiation Environment Model (MSSREM) peak flux model will be discussed. MSSREM uses probabilistic modeling techniques to build a design reference environment that can be tailored to a user specified mission start date, mission duration, and confidence level. The model can be run for any space mission outside the Earth's magnetic field and 1 AU from the sun during the years 1953-2055**. July 4, 2012**

The Critical Role of the Research Community in Space Weather Planning and Execution

Robert M. **Robinson** , Richard A. Behnke, Therese Moretto

Space Weather Volume 16, Issue 3, Pages: 200-204, March **2018**

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2017SW001778

The explosion of interest in space weather in the last 25 years has been due to a confluence of efforts all over the globe, motivated by the recognition that events on the Sun and the consequent conditions in interplanetary space and Earth's magnetosphere, ionosphere, and thermosphere can have serious impacts on vital technological systems. The fundamental research conducted at universities, government laboratories, and in the private sector has led to tremendous improvements in the ability to forecast space weather events and predict their impacts on human technology and health. The mobilization of the research community that made this progress possible was the result of a series of actions taken by the National Science Foundation (NSF) to build a national program aimed at space weather. The path forward for space weather is to build on those successes through continued involvement of the research community and support for programs aimed at strengthening basic research and education in academia, the private sector, and government laboratories. Investments in space weather are most effective when applied at the intersection of research and applications. Thus, to achieve the goals set forth originally by the National Space Weather Program, the research community must be fully engaged in the planning, implementation, and execution of space weather activities, currently being coordinated by the Space Weather Operations, Research, and Mitigation Subcommittee under the National Science and Technology Council.

Global Muon Detector Network Used for Space Weather Applications

M. **Rockenbach**, A. Dal Lago, N. J. Schuch, K. Munakata, T. Kuwabara, A. G. Oliveira, E. Echer, C. R. Braga, R. R. S. Mendonça, C. Kato, … show all 19

Space Science Reviews, August **2014**, Volume 182, Issue 1-4, pp 1-18

In this work, we summarize the development and current status of the Global Muon Detector Network (GMDN). The GMDN started in 1992 with only two muon detectors. It has consisted of four detectors since the Kuwait-city muon hodoscope detector was installed in March 2006. The present network has a total of 60 directional channels with an improved coverage of the sunward Interplanetary Magnetic Field (IMF) orientation, making it possible to continuously monitor cosmic ray precursors of geomagnetic storms. The data analysis methods developed also permit precise calculation of the three dimensional cosmic ray anisotropy on an hourly basis free from the atmospheric temperature effect and analysis of the cosmic ray precursors free from the diurnal anisotropy of the cosmic ray intensity.

A SEARCH FOR PERIODICITIES IN F10.7 SOLAR RADIO FLUX DATA

Soumya **Roy**, Prasad A., Panja S.Ch., Ghosh K., Patra S.N.

АСТРОНОМИЧЕСКИЙ ВЕСТНИК Том: 53Номер: 3 Год: **2019** Страницы: 240

The radio frequency emission at 10.7 cm (or 2800 MHz) wavelength (considered as solar flux density) out of different possible wavelengths is usually selected to identify periodicities because of its high correlation with solar extreme ultraviolet radiation as well as its complete and long observational record other than sunspot related indices. The solar radio flux at 10.7 cm wavelength plays a very valuable role for forecasting the space weather because it is originated from lower corona and chromospheres region of the Sun. Also, solar radio flux is a magnificent indicator of major solar activity. Here in the present work the solar radio flux data from 1965 to 2014 observed at the Domimion Radio Astrophysical Observatory in Penticton, British Columbia has been processed using Date Compensated Discrete Fourier Transform (DCDFT) to identify predominant periods within the data along with their confidence levels. Also, the multi-taper method (MTM) for periodicity analysis is used to validate the observed periods...

Prediction of Solar Proton Events with Machine Learning: Comparison with Operational Forecasts and "All-Clear" Perspectives

Viacheslav **Sadykov**, Alexander Kosovichev, Irina Kitiashvili, Vincent Oria, Gelu M Nita, Egor Illarionov, Patrick O'Keefe, Yucheng Jiang, Sheldon Fereira, Aatiya Ali

ApJ **2021**

https://arxiv.org/pdf/2107.03911.pdf

Solar Energetic Particle events (SEPs) are among the most dangerous transient phenomena of solar activity. As hazardous radiation, SEPs may affect the health of astronauts in outer space and adversely impact current and future space exploration. In this paper, we consider the problem of daily prediction of Solar Proton Events (SPEs) based on the characteristics of the magnetic fields in solar Active Regions (ARs), preceding soft X-ray and proton fluxes, and statistics of solar radio bursts. The machine learning (ML) algorithm uses an artificial neural network of custom architecture designed for whole-Sun input. The predictions of the ML model are compared with the SWPC NOAA operational forecasts of SPEs. Our preliminary results indicate that 1) for the AR-based predictions, it is necessary to take into account ARs at the western limb and on the far side of the Sun; 2) characteristics of the preceding proton flux represent the most valuable input for prediction; 3) daily median characteristics of ARs and the counts of type II, III, and IV radio bursts may be excluded from the forecast without performance loss; and 4) ML-based forecasts outperform SWPC NOAA forecasts in situations in which missing SPE events is very undesirable. The introduced approach indicates the possibility of developing robust "all-clear" SPE forecasts by employing machine learning methods.

Radiation Data Portal: Integration of Radiation Measurements at the Aviation Altitudes and Solar-Terrestrial Environment Observations

V.M. **Sadykov** , I.N. Kitiashvili , W. K. Tobiska , M. Guhathakurta

Space Weather **Volume19, Issue1** 2020SW002653 **2021**

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https://arxiv.org/pdf/2103.07604

The impact of radiation dramatically increases at high altitudes in the Earth's atmosphere and in space. Therefore, monitoring and access to radiation environment measurements are critical for estimating the radiation exposure risks of aircraft and spacecraft crews and the impact of space weather disturbances on electronics. Addressing these needs requires convenient access to multi-source radiation environment data and enhancement of visualization and search capabilities. The Radiation Data Portal represents an interactive web-based application for search and visualization of in-flight radiation measurements. The Portal enhances the exploration capabilities of various properties of the radiation environment and provides measurements of dose rates along with information on space weather-related conditions. The Radiation Data Portal back-end is a MySQL relational database that contains the radiation measurements obtained from the Automated Radiation Measurements for Aerospace Safety (ARMAS) device and the soft X-ray and proton flux measurements from the Geostationary Operational Environmental Satellite (GOES). The implemented Application Programming Interface (API) and Python routines allow a user to retrieve the database records without interaction with the web interface. As a use case of the Radiation Data Portal, we examine ARMAS measurements during an enhancement of the Solar Proton (SP) fluxes, known as Solar Proton Events (SPEs), and compare them to measurements during SP-quiet periods. **4-7 Sep 2017**

4. Enhanced Solar Proton Environment

Reconstruction of the Radiation Belts for Solar Cycles 17–24 (1933–2017)

A. A. **Saikin** , Y. Y. Shprits , A. Y. Drozdov , D. A. Landis , I. S. Zhelavskaya , S. Cervantes
Space Weather Volume19, Issue3 March **2021** e2020SW002524
https://doi.org/10.1029/2020SW002524
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020SW002524
We present a reconstruction of the dynamics of the radiation belts from solar cycles 17 to 24 which allows us to study how radiation belt activity has varied between the different solar cycles. The radiation belt simulations are produced using the Versatile Electron Radiation Belt (VERB)-3D code. The VERB-3D code simulations incorporate radial, energy, and pitch angle diffusion to reproduce the radiation belts. Our simulations use the historical measurements of Kp (available since solar cycle 17, i.e., 1933) to model the evolution radiation belt dynamics between L* = 1–6.6. A nonlinear auto regressive network with exogenous inputs (NARX) neural network was trained off GOES 15 measurements (January 2011–March 2014) and used to supply the upper boundary condition (L* = 6.6) over the course of solar cycles 17–24 (i.e., 1933–2017). Comparison of the model with long term observations of the Van Allen Probes and CRRES demonstrates that our model, driven by the NARX boundary, can reconstruct the general evolution of the radiation belt fluxes. Solar cycle 24 (January 2008–2017) has been the least active of the considered solar cycles which resulted in unusually low electron fluxes. Our results show that solar cycle 24 should not be used as a representative solar cycle for developing long term environment models. The developed reconstruction of fluxes can be used to develop or improve empirical models of the radiation belts.

Geomagnetic response to solar and interplanetary disturbances **Review**

E. **Saiz**1, Y. Cerrato1, C. Cid1, V. Dobrica2, P. Hejda3, P. Nenovski4, P. Stauning5, J. Bochnicek3, D. Danov6, C. Demetrescu2, W. D. Gonzalez7, G. Maris2, D.
Teodosiev6, F. Valach8
Journal of Space Weather and Space Climate · July **2013** 3 A26
http://sci-hub.tw/10.1051/swsc/2013048
The space weather discipline involves different physical scenarios, which are characterized by very different physical conditions, ranging from the Sun to the terrestrial magnetosphere and ionosphere. Therefore, development of a comprehensive model to explain the entire Sun–Earth chain is presently still far from completion. However, the effects of solar activity on our modern technological infrastructure have clearly demonstrated the need for accurate space weather services to address a broad spectrum of user needs. A key element for completion of this task is to push for advances in our knowledge of solar–terrestrial physics. This review paper focuses on the geomagnetic response to solar and interplanetary disturbances. Following a description of their long-term evolution, we discuss short-term responses, where we distinguish between responses of the terrestrial environment to solar activity (and specifically to solar energetic events) and to the solar wind. Geomagnetic responses at low and high latitudes are considered separately. At low latitudes, the evolution of the ring current in both the main and recovery phases is discussed. At high latitudes, achievements in modelling the coupling between magnetospheric and ionospheric processes are described, with special attention to the polar caps and field-aligned currents.

Impact of space environment on geostationary meteorological satellite data outage

Kaori **Sakaguchi**,Tsutomu Nagatsuma
Space Weather **Volume20, Issue5** e2021SW002965 **2022**
https://doi.org/10.1029/2021SW002965
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021SW002965
Impact of space environment changes on geostationary meteorological satellite services, such as data outage, incomplete imagery, or quality degradation were investigated using event logs of Himawari-8 and Meteosat (MET-7 and MET-8) in 2015–2017. The event logs show that such failures were caused by anomalies on spacecraft and in ground system half each. On Himawari-8, a total of 11 incomplete imagery occurred due to spacecraft anomaly, and among them about 45% (5 anomalies) occurred during energetic electron enhancement and about 9% (1 anomaly) occurred during energetic proton enhancement. In cases of Meteosat, a total of 84 service alerts occurred due to spacecraft anomaly, and among them 35% (29 anomalies) occurred during electron enhancement and 7% (6 anomalies) occurred during both proton and electron enhancement. On the basis of statistical analysis, it is found that the probability of spacecraft anomaly occurrence markedly increases when electron fluence exceeds a threshold. The probability of anomaly is less than 10% when the 1-MeV electron fluence is less than 104 [/cm2 sr eV], whereas it increases to more than 20% above the fluence. Thresholds are also found for electron fluences at other energies from 200 keV to 1.5 MeV. This study clarifies that changes in the space environment, particularly electron fluence enhancement affect geostationary meteorological satellite services.

Prediction of Space Weather Events through Analysis of Active Region Magnetograms using Convolutional Neural Network

Shlesh **Sakpal**

2024

https://arxiv.org/pdf/2405.02545

Although space weather events may not directly affect human life, they have the potential to inflict significant harm upon our communities. Harmful space weather events can trigger atmospheric changes that result in physical and economic damages on a global scale. In 1989, Earth experienced the effects of a powerful geomagnetic storm that caused satellites to malfunction, while triggering power blackouts in Canada, along with electricity disturbances in the United States and Europe. With the solar cycle peak rapidly approaching, there is an ever-increasing need to prepare and prevent the damages that can occur, especially to modern-day technology, calling for the need of a comprehensive prediction system. This study aims to leverage machine learning techniques to predict instances of space weather (solar flares, coronal mass ejections, geomagnetic storms), based on active region magnetograms of the Sun. This was done through the use of the NASA DONKI service to determine when these solar events occur, then using data from the NASA Solar Dynamics Observatory to compile a dataset that includes magnetograms of active regions of the Sun 24 hours before the events. By inputting the magnetograms into a convolutional neural network (CNN) trained from this dataset, it can serve to predict whether a space weather event will occur, and what type of event it will be. The model was designed using a custom architecture CNN, and returned an accuracy of 90.27%, a precision of 85.83%, a recall of 91.78%, and an average F1 score of 92.14% across each class (Solar flare [Flare], geomagnetic storm [GMS], coronal mass ejection [CME]). Our results show that using magnetogram data as an input for a CNN is a viable method to space weather prediction. Future work can involve prediction of the magnitude of solar events.

Forecasting Periods of Strong Southward Magnetic Field Following Interplanetary Shocks

T. M. **Salman** N. Lugaz C. J. Farrugia R. M. Winslow A. B. Galvin N. A. Schwadron

Space Weather 16?, 12, 2004-2021 **2018**

http://sci-hub.tw/10.1029/2018SW002056

Long periods of strong southward magnetic fields are known to be the primary cause of intense geomagnetic storms. The majority of such events are caused by the passage over Earth of a magnetic ejecta. Irrespective of the interplanetary cause, fast-forward shocks often precede such strong southward Bz periods. Here we first look at all long periods of strong southward magnetic fields as well as fast-forward shocks measured by the Windspacecraft in a 22.4-year span. We find that 76% of strong southward Bz periods are preceded within 48 hr by at least a fast-forward shock, but only about 23% of all shocks are followed within 48 hr by strong southward Bz periods. Then, we devise a threshold-based probabilistic forecasting method based on the shock properties and the pre-shock near-Earth solar wind plasma and interplanetary magnetic field characteristics adopting a superposed epoch analysis-like approach. Our analysis shows that the solar wind conditions in the 30-min interval around the arrival of fast-forward shocks have a significant contribution to the prediction of long-duration southward Bz periods. This probabilistic model may provide on average a 14-hr warning time for an intense and long-duration southward Bz period. Evaluating the forecast capability of the model through a statistical and skill score-based approach reveals that it outperforms a coin-flipping forecast. By using the information provided by the arrival of a fast-forward shock at L1, this model represents a marked improvement over similar forecasting methods. We outline a number of future potential improvements.

Implementing the MULTI-VP coronal model in EUHFORIA: test case results and comparisons with the WSA coronal model

Evangelia **Samara**, Rui F. Pinto, Jasmina Magdalenic, Nicolas Wijsen, Veronika Jercic, Camilla Scolini, Immanuel C. Jebaraj, Luciano Rodriguez, Stefaan Poedts

A&A 648, A35 **2021**

https://arxiv.org/pdf/2102.06617.pdf

https://www.aanda.org/articles/aa/pdf/2021/04/aa39325-20.pdf

https://doi.org/10.1051/0004-6361/202039325

In this study, we focus on improving EUHFORIA (European Heliospheric Forecasting Information Asset), a recently developed 3D MHD space weather prediction tool. EUHFORIA consists of two parts, covering two spatial domains; the solar corona and the inner heliosphere. For the first part, the semi-empirical Wang-Sheeley-Arge (WSA) model is used by default, which employs the Potential Field Source Surface (PFSS) and Schatten Current Sheet (SCS) models to provide the necessary solar wind plasma and magnetic conditions above the solar surface, at 0.1 AU, that serve as boundary conditions for the inner heliospheric part. Herein, we present the first results of the implementation of an alternative coronal model in EUHFORIA, the so-called MULTI-VP model. We compared the output of the default coronal model with the output from MULTI-VP at the inner boundary of the heliospheric domain of EUHFORIA in order to understand differences between the two models, before they propagate to Earth. We also compared the performance of WSA+EUHFORIA-heliosphere and MULTI-VP+EUHFORIA-heliosphere against in situ observations at Earth. In the frame of this study, we considered two different high-speed stream cases, one during a period of low solar activity and one during a period of high solar activity. We also employed two different magnetograms, i.e., GONG and WSO. Our results show that the choice of both the coronal model and the magnetogram play an important role on the accuracy of the solar wind prediction. However, it is not clear which component plays the most important role for the modeled results obtained at Earth. A statistical analysis with an appropriate number of simulations is needed to confirm our findings. **2011-06-20-22, 2018-01-17-21, 2018-05-05**

Solar Radio Burst events on September 6, 2017 and its impact on GNSS signal frequencies

H. **Sato** , N. Jakowski , J. Berdermann, K. Jiricka , A. Heßelbarth , D. Banys, V. Wilken

Space Weather **Volume17, Issue6** Pages 816-826 **2019**

sci-hub.se/10.1029/2019SW002198

During the intense solar radio bursts on **September 6, 2017**, GNSS signal interferences were observed at ground stations in the European longitude sector from 20°N to 70°N for all GNSS satellites in view including GPS, GLONASS and Galileo. The solar radio noise reduced the signal-to-noise ratio (SNR) with clear frequency dependence. The impact of the radio burst has been found at L2 and L5 frequencies, but not at L1 frequency. The ground observation of the solar radio spectrum between 1.0–2.0 GHz corresponds well to such frequency dependence. The maximum SNR reduction of **-**10 dB was found when the solar radio flux was pulsating around 2000 SFU level. Precise Point Positioning (PPP) results show that accuracy is reduced with stronger deviation for dual-frequency solutions than for single-frequency solutions based on L1 signal only. The positioning error refers rather to the solar EUV flare than to solar radio interferences. The results presented here are a clear indication of frequency-dependent GNSS performance degradation during strong space weather events.

Nowcast and forecast of galactic cosmic ray (GCR) and solar energetic particle (SEP) fluxes in magnetosphere and ionosphere – Extension of WASAVIES to Earth orbit

Tatsuhiko **Sato**, Ryuho Kataoka, Daikou Shiota, Yûki Kubo, Mamoru Ishii, Hiroshi Yasuda, Shoko Miyake, Yoshizumi Miyoshi, Haruka Ueno and Aiko Nagamatsu

J. Space Weather Space Clim. **2019**, 9, A9

https://www.swsc-journal.org/articles/swsc/pdf/2019/01/swsc180058.pdf

Real-time estimation of cosmic-ray fluxes on satellite orbits is one of the greatest challenges in space weather research. Therefore, we develop a system for nowcasting and forecasting the galactic cosmic ray (GCR) and solar energetic particle (SEP) fluxes at any location in the magnetosphere and ionosphere during ground-level enhancement (GLE) events. It is an extended version of the WArning System for AVIation Exposure to SEP (WASAVIES), which can determine event profiles by using real-time data of the count rates of several neutron monitors (NMs) at the ground level and high-energy proton fluxes observed by Geostationary Operational Environmental Satellites (GOES) satellites. The extended version, called WASAVIES-EO, can calculate the GCR and SEP fluxes outside a satellite based on its two-line element (TLE) data. Moreover, organ absorbed-dose and dose-equivalent rates of astronauts in the International Space Station (ISS) can be estimated using the system, considering its shielding effect. The accuracy of WASAVIES-EO was validated based on the dose rates measured in ISS, as well as based on high-energy proton fluxes observed by POES satellites during large GLEs that have occurred in the 21st century. Agreement between the nowcast and forecast dose rates in ISS, especially in terms of their temporal structures, indicates the usefulness of the developed system for future mission operations. **2001/4/15, 2005/1/20, 2006/12/13, 2012/5/17, 2017/9/10**

Real Time and Automatic Analysis Program for WASAVIES: Warning System for Aviation Exposure to Solar Energetic Particles

Tatsuhiko **Sato**, Ryuho Kataoka, Daikou Shiota, Yûki Kubo , Mamoru Ishii, Hiroshi Yasuda, Shoko Miyake , In Chun Park , Yoshizumi Miyoshi

Space Weather Volume16, Issue7 July **2018** Pages 924-936

http://sci-hub.tw/10.1029/2018SW001873

A physics-based warning system for aviation exposure to solar energetic particles, WASAVIES, is improved to be capable of real-time and automatic analysis. In the improved system, the count rates of several neutron monitors at the ground level, as well as the proton fluxes measured by the Geostationary Operational Environmental Satellite (GOES), are continuously downloaded at intervals of 5 min and used for checking the occurrence of ground level enhancement (GLE). When a GLE event is detected, the system automatically determines the model parameters for characterizing the profiles of each GLE event and nowcasts and forecasts the radiation dose rates all over the world up to 24 hr after the flare onset. The performance of WASAVIES is examined by analyzing the four major GLE events of the 21st century. The accuracy of the nowcast data obtained by the model is well validated by the

reproducibility of the current neutron monitor count rates and GOES proton fluxes as well as the flight-dose measurements. On the other hand, the forecast data are reliable only when the evaluated parameters are stable, as expected in the model. A Web interface of WASAVIES is also developed and will be released in the near future through the public server of National Institute of Information and Communications Technology (NICT).
GLEs 2001/4/15, Jan. 20, 2005, 2006/12/13, 2012/5/17
This article is a companion to **Kataoka et al. (2018)** https://doi.org/10.1029/2018SW001874.

Global mapping of ionospheric HF/VHF radio wave absorption due to solar energetic protons

Herbert H. **Sauer**, Daniel C. Wilkinson
SPACE WEATHER, VOL. 6, S12002, doi:10.1029/2008SW000399, 2008
http://www.agu.org/pubs/crossref/2008/2008SW000399.shtml
Simple, one-parameter algorithms are applied to the observed energetic proton flux as provided by instruments aboard the GOES series of satellites to yield estimates of the high-latitude HF and VHF radio wave absorption for day and night, respectively. These results are extended to full daily coverage by treating the effects of solar illumination, geomagnetic cutoff variation, and frequency dependence over the entire earth. Validation calculations of the polar cap absorption of HF radio waves have been performed for 11 larger solar energetic particle events during the period from 1992 to 2002 and the results are compared to observations of 30 MHz riometers operated by the Air Force Geophysics Laboratory and located at Thule, Greenland. Prediction of the minimum event duration from current flux level is also obtained, and a specimen presentation of the north and south polar caps illustrates the graphical output of the model for the peak of the 6 December 2006 solar proton event.

Predicting the magnetic vectors within coronal mass ejections arriving at Earth 1. Initial architecture

Savani, N. P.; Vourlidas, A.; Szabo, A.; Mays, M. L.; Thompson, B. J.; Richardson, I. G.; Evans, R.; Pulkkinen, A.; Nieves-Chinchilla, T.
Space Weather , Volume 13, Issue 6 June **2015** Pages 374–385**,**
http://arxiv.org/pdf/1502.02067v1.pdf **File**
http://onlinelibrary.wiley.com/doi/10.1002/2015SW001171/full
The process by which the Sun affects the terrestrial environment on short timescales is predominately driven by the amount of magnetic reconnection between the solar wind and Earth's magnetosphere. Reconnection occurs most efficiently when the solar wind magnetic field has a southward component. The most severe impacts are during the arrival of a coronal mass ejection (CME) when the magnetosphere is both compressed and magnetically connected to the heliospheric environment. Unfortunately, forecasting magnetic vectors within coronal mass ejections remain elusive. Here we report how, by combining a statistically robust helicity rule for a CME's solar origin with a simplified flux rope topology, the magnetic vectors within the Earth-directed segment of a CME can be predicted. In order to test the validity of this proof-of-concept architecture for estimating the magnetic vectors within CMEs, a total of eight CME events (between 2010 and 2014) have been investigated. With a focus on the large false alarm of **January 2014**, this work highlights the importance of including the early evolutionary effects of a CME for forecasting purposes. The angular rotation in the predicted magnetic field closely follows the broad rotational structure seen within the in situ data. This time-varying field estimate is implemented into a process to quantitatively predict a time-varying Kp index that is described in detail in paper II. Future statistical work, quantifying the uncertainties in this process, may improve the more heuristic approach used by early forecasting systems.

Predicting the magnetic vectors within coronal mass ejections arriving at Earth: 2. Geomagnetic response

N. P. **Savani**, A. Vourlidas, I. G. Richardson, A. Szabo, B. J. Thompson, A. Pulkkinen, M. L. Mays, T. Nieves-Chinchilla, V. Bothmer
Space Weather Volume 15, Issue 2 February **2017** Pages 441–461
DOI: 10.1002/2016SW001458
http://onlinelibrary.wiley.com/doi/10.1002/2016SW001458/full
http://sci-hub.se/10.1002/2016SW001458
This is a companion to Savani et al. (2015) that discussed how a first-order prediction of the internal magnetic field of a coronal mass ejection (CME) may be made from observations of its initial state at the Sun for space weather forecasting purposes (Bothmer-Schwenn scheme (BSS) model). For eight CME events, we investigate how uncertainties in their predicted magnetic structure influence predictions of the geomagnetic activity. We use an empirical relationship between the solar wind plasma drivers and Kp index together with the inferred magnetic vectors, to make a prediction of the time variation of Kp (Kp(BSS)). We find a 2σ uncertainty range on the magnetic field magnitude (|B|) provides a practical and convenient solution for predicting the uncertainty in geomagnetic storm strength. We also find the estimated CME velocity is a major source of error in the predicted maximum Kp.

The time variation of Kp(BSS) is important for predicting periods of enhanced and maximum geomagnetic activity, driven by southerly directed magnetic fields, and periods of lower activity driven by northerly directed magnetic field. We compare the skill score of our model to a number of other forecasting models, including the NOAA/Space Weather Prediction Center (SWPC) and Community Coordinated Modeling Center (CCMC)/SWRC estimates. The BSS model was the most unbiased prediction model, while the other models predominately tended to significantly overforecast. The True skill score of the BSS prediction model (TSS = 0.43 ± 0.06) exceeds the results of two baseline models and the NOAA/SWPC forecast. The BSS model prediction performed equally with CCMC/SWRC predictions while demonstrating a lower uncertainty.

3 Apr 2010, 25 Mar 2011, 10 Mar 2012, 14 Jun 2012, 12 Jul 2012, 27 Sep 2012, 7 Jan 2014, 10 Sep 2014

Discussion on the spectral coherence between planetary, solar and climate oscillations: a reply to some critiques

Nicola **Scafetta**

2014

During the last few years a number of works have proposed that planetary harmonics regulate solar oscillations and the Earth climate. Herein I address some critiques. Detailed analysis of the data do support the planetary theory of solar and climate variation. In particular, I show that: (1) high-resolution cosmogenic 10Be and 14C solar activity proxy records both during the Holocene and during the Marine Interglacial Stage 9.3 (MIS 9.3), 325-336 kyr ago, present four common spectral peaks at about 103, 115, 130 and 150 yrs (this is the frequency band that generates Maunder and Dalton like grand solar minima) that can be deduced from a simple solar model based on a generic non-linear coupling between planetary and solar harmonics; (2) time-frequency analysis and advanced minimum variance distortion-less response (MVDR) magnitude squared coherence analysis confirm the existence of persistent astronomical harmonics in the climate records at the decadal and multidecadal scales when used with an appropriate window length (110 years) to guarantee a sufficient spectral resolution. However, the best coherence test can be currently made only by comparing directly the temperature and astronomical spectra as done in Scafetta (J. Atmos. Sol. Terr. Phys. 72(13), 951-970, 2010). The spectral coherence between planetary, solar and climatic oscillations is confirmed at the following periods: 5.2 yr, 5.93 yr, 6.62 yr, 7.42 yr, 9.1 yr (main lunar tidal cycle), 10.4 yr (related to the 9.93-10.87-11.86 yr solar cycle harmonics), 13.8-15.0 yr, 20 yr, 30 yr and 61 yr, 103 yr, 115 yr, 130 yr, 150 yr and about 1000 year. This work responds to the critiques of Cauquoin et al. (Astron. Astrophys. 561, A132, 2014) who ignored alternative planetary theories of solar variations, and of Holm (J. Atmos. Sol. Terr. Phys. 110-111, 23-27, 2014) who used inadequate physical and time frequency analysis of the data.

O+ escape during the extreme space weather event of September 4–10, 2017

Audrey **Schillings**, Hans Nilsson, Rikard Slapak, Peter Wintoft, , Masatoshi Yamauchi, Magnus Wik, Iannis S Dandouras, Christopher M. Carr

Space Weather **2018**

https://sci-hub.tw/10.1029/2018SW001881

We have investigated the consequences of extreme space weather on ion outflow from the polar ionosphere by analyzing the solar storm that occurred early September 2017, causing a severe geomagnetic storm. Several X-flares and coronal mass ejections (CMEs) were observed between 4 and 10 September. The first shock – likely associated with a CME – hit the Earth late on September 6, produced a storm sudden commencement (SSC) and began the initial phase of the storm. It was followed by a second shock, approximately 24h later, that initiated the main phase and simultaneously the Dst index dropped to Dst = −142 nT and Kp index reached Kp = 8. Using CODIF data onboard Cluster satellite 4, we estimated the ionospheric O+ outflow before and after the second shock. We found an enhancement in the polar cap by a factor of 3 for an unusually high ionospheric O+ outflow (mapped to an ionospheric reference altitude) of 1013 m−2s−1. We suggest that this high ionospheric O+ outflow is due to a preheating of the ionosphere by the multiple X-flares. Finally, we briefly discuss the space weather consequences on the magnetosphere as a whole and the enhanced O+ outflow in *connection with enhanced satellite drag.*

Changes in the Total Solar Irradiance and climatic effects

Werner K. **Schmutz***

J. Space Weather Space Clim. **2021**, 11, 40

https://www.swsc-journal.org/articles/swsc/pdf/2021/01/swsc200108.pdf

https://doi.org/10.1051/swsc/2021016

The correlation between the averaged reconstructed March temperature record for Kyoto, Japan, and the reconstructed Total Solar Irradiance (TSI) irradiance over 660 years from 1230 to 1890 gives evidence with 98% probability that the Little Ice Age with four cold periods is forced by variations of TSI. If the correlation is restricted to the period 1650–1890, with two cold periods in the 17th and 19th century and for which two independent reconstructed March temperature records are available, the probability of solar forcing increases to 99.99%. As solar irradiance variations have a global effect there has to be a global climatic solar forcing impact. However, by how much global temperature were lower during these minima and with what amplitude TSI was varying is not accurately known. The two quantities, global temperature and TSI, are linked by the energy equilibrium equation for the Earth system. The derivation of this equation with respect to a variation of the solar irradiance has two terms: A direct forcing term, which can be derived analytically and quantified accurately from the Stefan-Boltzmann law, and a second term, describing indirect influences on the surface temperature. If a small TSI variation should force a large temperature variation, then it has to be the second indirect term that strongly amplifies the effect of the direct forcing. The current knowledge is summarized by three statements:

- During the minima periods in the 13th, 15/16th, 17th, and 19th centuries the terrestrial climate was colder by 0.5–1.5 °C;
- Indirect Top-down and Bottom-up mechanisms do not amplify direct forcing by a large amount, i.e. indirect solar forcing is of the same magnitude (or smaller) as direct solar forcing;
- The radiative output of the Sun cannot be lower by more than 2 Wm−2 below the measured present-day TSI value during solar cycle minimum.

These three statements contradict each other and it is concluded that at least one is not correct. Which one is a wrong statement is presently not known conclusively. It is argued that it is the third statement and it is speculated that over centennial time scales the Sun might vary its radiance significantly more than observed so far during the last 40 years of space TSI measurements. To produce Maunder minimum type cold climate excursions, a TSI decrease of the order of 10 Wm−2 is advocated.

Socio-economic hazards and impacts of space weather: the important range between mild and extreme **Review**

Carolus J. **Schrijver**

Space Weather **13**: 524–528 **2015**
http://arxiv.org/pdf/1507.08730v1.pdf
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2015SW001252
https://doi.org/10.1002/2015SW001252

Society needs to prepare for more severe space weather than it has experienced in the modern technological era. To enable that, we must both quantify extreme-event characteristics and analyze impacts of lesser events that are frequent yet severe enough to be informative. Exploratory studies suggest that economic impacts of a century-level space hurricane and of a century of lesser space-weather "gales" may turn out to be of the same order of magnitude. The economic benefits of effective mitigation of the impacts of space gales may substantially exceed the required investments, even as these investments provide valuable information to prepare for the worst possible storms.

Understanding space weather to shield society: A global road map for 2015–2025 commissioned by COSPAR and ILWS **Review**

Carolus J. **Schrijver**, , , Kirsti Kauristieb, , Alan D. Aylwardc, Clezio M. Denardinid, Sarah E. Gibsone, Alexi Gloverf, Nat Gopalswamyg, Manuel Grandeh, Mike Hapgoodi, Daniel Heynderickxj, Norbert Jakowskik, Vladimir V. Kalegaevl, Giovanni Lapentam, Jon A. Linkern, Siqing Liuo, Cristina H. Mandrinip, Ian R. Mannq, Tsutomu Nagatsumar, Dibyendu Nandys, Takahiro Obarat, T. Paul O'Brienu, Terrance Onsagerv, Hermann J. Opgenoorthw, Michael Terkildsenx, Cesar E. Valladaresy, Nicole Vilmerz

Advances in Space Research Volume 55, Issue 12, 15 June **2015**, Pages 2745–2807, **File**
https://files.mail-list.com/m/iswinewsletter/Understanding-space-weather.pdf

There is a growing appreciation that the environmental conditions that we call space weather impact the technological infrastructure that powers the coupled economies around the world. With that comes the need to better shield society against space weather by improving forecasts, environmental specifications, and infrastructure design. We recognize that much progress has been made and continues to be made with a powerful suite of research observatories on the ground and in space, forming the basis of a Sun–Earth system observatory. But the domain of space weather is vast – extending from deep within the Sun to far outside the planetary orbits – and the physics complex – including couplings between various types of physical processes that link scales and domains from the microscopic to large parts of the solar system. Consequently, advanced understanding of space weather requires a coordinated international approach to effectively provide awareness of the processes within the Sun–Earth system through observation-driven models. This roadmap prioritizes the scientific focus areas and research infrastructure that are needed to significantly advance our understanding of space weather of all intensities and of its implications

for society. Advancement of the existing system observatory through the addition of small to moderate state-of-the-art capabilities designed to fill observational gaps will enable significant advances. Such a strategy requires urgent action: key instrumentation needs to be sustained, and action needs to be taken before core capabilities are lost in the aging ensemble. We recommend advances through priority focus (1) on observation-based modeling throughout the Sun–Earth system, (2) on forecasts more than 12 h ahead of the magnetic structure of incoming coronal mass ejections, (3) on understanding the geospace response to variable solar-wind stresses that lead to intense geomagnetically-induced currents and ionospheric and radiation storms, and (4) on developing a comprehensive specification of space climate, including the characterization of extreme space storms to guide resilient and robust engineering of technological infrastructures. The roadmap clusters its implementation recommendations by formulating three action pathways, and outlines needed instrumentation and research programs and infrastructure for each of these. An executive summary provides an overview of all recommendations.

Understanding space weather to shield society: A global road map for 2015-2025 commissioned by COSPAR and ILWS **Review**

Carolus J. **Schrijver**, Kirsti Kauristie, Alan D. Aylward, Clezio M. Denardini, Sarah E. Gibson, Alexi Glover, Nat Gopalswamy, Manuel Grande, Mike Hapgood, Daniel Heynderickx, Norbert Jakowski,Vladimir V. Kalegaev, Giovanni Lapenta, Jon A. Linker, Siqing Liu, Cristina H. Mandrini, Ian R. Mann,Tsutomu Nagatsuma, Dibyendu Nandi, Takahiro Obara, T. Paul O'Brien, Terrance Onsager, Hermann J. Opgenoorth, Michael Terkildsen, Cesar E. Valladares, Nicole Vilmer

Advances of Space Research v. 55 p. 2745–2807 **2015**

http://arxiv.org/pdf/1503.06135v1.pdf

http://www.sciencedirect.com/science/article/pii/S0273117715002252

There is a growing appreciation that the environmental conditions that we call space weather impact the technological infrastructure that powers the coupled economies around the world. With that comes the need to better shield society against space weather by improving forecasts, environmental specifications, and infrastructure design. [...] advanced understanding of space weather requires a coordinated international approach to effectively provide awareness of the processes within the Sun-Earth system through observation-driven models. This roadmap prioritizes the scientific focus areas and research infrastructure that are needed to significantly advance our understanding of space weather of all intensities and of its implications for society. Advancement of the existing system observatory through the addition of small to moderate state-of-the-art capabilities designed to fill observational gaps will enable significant advances. Such a strategy requires urgent action: key instrumentation needs to be sustained, and action needs to be taken before core capabilities are lost in the aging ensemble. We recommend advances through priority focus (1) on observation-based modeling throughout the Sun-Earth system, (2) on forecasts more than 12 hrs ahead of the magnetic structure of incoming coronal mass ejections, (3) on understanding the geospace response to variable solar-wind stresses that lead to intense geomagnetically-induced currents and ionospheric and radiation storms, and (4) on developing a comprehensive specification of space climate, including the characterization of extreme space storms to guide resilient and robust engineering of technological infrastructures. The roadmap clusters its implementation recommendations by formulating three action pathways, and outlines needed instrumentation and research programs and infrastructure for each of these. [...]

Assessing the impact of space weather on the electric power grid based on insurance claims for industrial electrical equipment

C.J. **Schrijver**, R. Dobbins, W. Murtagh, S.M. Petrinec

E-print, June **2014**; Space Weather Journal

http://www.lmsal.com/~schryver/Public/ms/SWx_insuranceclaims_SWJ2014.pdf

http://onlinelibrary.wiley.com/doi/10.1002/SWQv11i003/pdf

Geomagnetically induced currents are known to induce disturbances in the electric power grid. Here, we perform a statistical analysis of 11,242 insurance claims from 2000 through 2010 for equipment losses and related business interruptions in North-American commercial organizations that are associated with damage to, or malfunction of, electrical and electronic equipment. We find that claims rates are elevated on days with elevated geomagnetic activity by approximately 20% for the top 5%, and by about 10% for the top third of most active days ranked by daily maximum variability of the geomagnetic field. When focusing on the claims explicitly attributed to electrical surges (amounting to more than half the total sample), we find that the dependence of claims rates on geomagnetic activity mirrors that of major disturbances in the U.S. high-voltage electric power grid. The claims statistics thus reveal that large-scale geomagnetic variability couples into the low-voltage power distribution network and that related power-quality variations can cause malfunctions and failures in electrical and electronic devices that, in turn, lead to an estimated 500 claims per average year within North America. We discuss the possible magnitude of the full economic impact associated with quality variations in electrical power associated with space weather.

Space weather from explosions on the Sun: how bad could it be? **Review**

C.J. **Schrijver**, J. Beer

E-print, June **2014**; EOS, Vol. 95, No. 24, 17 June, **2014**

http://www.lmsal.com/~schryver/Public/ms/SchrijverBeer_EOS2014_final.pdf

How does one find out how severe extreme space weather can be? In this concise report we review the recent scientific literature on that topic, combining terrestrial, lunar, and stellar data. We find that solar flares, energetic particle storms, and geomagnetic disturbances can all be more intense than modern technology has experienced: flares could be hundreds of times more energetic, particle storms a few times more intense, and geomagnetic storms may exceed the strongest on record by a moderate factor. This publication summarizes the significant progress that has been made recently on establishing the statistics of the worst space weather, and that there is more data available that can be used to improve upon that.

Disturbances in the U.S. electric grid associated with geomagnetic activity

C.J. **Schrijver** and S.D. Mitchell

E-print, May **2013**; Space Weather and Space Climate, 2013

Large solar explosions are responsible for space weather that can impact technological infrastructure on and around Earth. Here, we apply a retrospective cohort exposure analysis to quantify the impacts of geomagnetic activity on the U.S. electric power grid for the period from 1992 through 2010. We find, with more than 3 sigma significance, that approximately 4% of the disturbances in the U.S. power grid reported to the U.S. Department of Energy are attributable to strong geomagnetic activity and its associated geomagnetically induced currents.

Estimating the frequency of extremely energetic solar events, based on solar, stellar, lunar, and terrestrial records

Schrijver, C. J.; Beer, J.; Baltensperger, U.; Cliver, E. W.; GƏdel, M.; Hudson, H. S.; McCracken, K. G.; Osten, R. A.; Peter, T.; Soderblom, D. R.; Usoskin, I. G.; Wolff, E. W.

J. Geophys. Res., Vol. 117, No. A8, A08103, **2012**

http://dx.doi.org/10.1029/2012JA017706

The most powerful explosions on the Sun – in the form of bright flares, intense storms of solar energetic particles (SEPs), and fast coronal mass ejections (CMEs) – drive the most severe space-weather storms. Proxy records of flare energies based on SEPs in principle may offer the longest time base to study infrequent large events. We conclude that one suggested proxy, nitrate concentrations in polar ice cores, does not map reliably to SEP events. Concentrations of select radionuclides measured in natural archives may prove useful in extending the time interval of direct observations up to ten millennia, but as their calibration to solar flare fluences depends on multiple poorly known properties and processes, these proxies cannot presently be used to help determine the flare energy frequency distribution. Being thus limited to the use of direct flare observations, we evaluate the probabilities of large-energy solar events by combining solar flare observations with an ensemble of stellar flare observations. We conclude that solar flare energies form a relatively smooth distribution from small events to large flares, while flares on magnetically active, young Sun-like stars have energies and frequencies markedly in excess of strong solar flares, even after an empirical scaling with the mean coronal activity level of these stars. In order to empirically quantify the frequency of uncommonly large solar flares extensive surveys of stars of near-solar age need to be obtained, such as is feasible with the Kepler satellite. Because the likelihood of flares larger than approximately X30 remains empirically unconstrained, we present indirect arguments, based on records of sunspots and on statistical arguments, that solar flares in the past four centuries have likely not substantially exceeded the level of the largest flares observed in the space era, and that there is at most about a 10% chance of a flare larger than about X30 in the next 30 years.

Heliophysics II. Space Sotrms and Radiation: Causes and Effects

Schrijver, C.J. and Siscoe,G.L. (eds.) **2010**, Cambridge University Press, Cambridge

Heliophysics is a fast-developing scientific discipline that integrates studies of the Sun's variability, the surrounding heliosphere, and the environment and climate of the planets. Over the past few centuries, our understanding of how the Sun drives space weather and climate on the Earth and other planets has advanced at an ever increasing rate. The Sun is a magnetically variable star and, for planets win intrinsic magnetic fields, planets with atmospheres, or planets like Earth with both, there are profound consequences. This volume, the the second in a series of three heliophysics texts, integrates the many aspects of space storms and the energetic radiation associated with them - from their causes on the Sun to their effects in planetary environments. It reviews the physical processes in solar flares and coronal mass ejections, interplanetary shocks, and particle acceleration and transport, and considers many of the space weather responses in geospace. Historical space weather observations, in-situ particle measurement techniques, radiative emissions from energetic particles, and impacts of space weather on people and technology in space are also reviewed. In addition to its utility as a textbook, it also constitutes a foundational reference for researchers in the fields of heliophysics, astrophysics, plasma physics, space physics, solar physics, aeronomy, space weather, planetary science, and climate science. Additional online resources, including lecture presentations and other teaching materials, can be accessed at **www.cambridge.org/9780521760515.**

Heliophysics III. Evolving Solar Activity and the Climates of Space and Earth

Schrijver, C.J. and Siscoe,G.L. (eds.) **2010**, Cambridge University Press, Cambridge

Solar energetic events, the solar-stellar connection, and statistics of extreme space weather

C.J. **Schrijver**

*ASP Conference Series, Vol. , **2010; File***

Observations of the Sun and of Sun-like stars provide access to different aspects of stellar magnetic activity that, when combined, help us piece together a more comprehensive picture than can be achieved from only the solar or the stellar perspective. Where the Sun provides us with decent spatial resolution of, e.g., magnetic bipoles and the overlying dynamic, hot atmosphere, the ensemble of stars enables us to see rare events on at least some occasions. Where the Sun shows us how flux emergence, dispersal, and disappearance occur in the complex mix of polarities on the surface, only stellar observations can show us the activity of the ancient or future Sun. In this review, I focus on a comparison of statistical properties, from bipolar-region emergence to flare energies, and from heliospheric events to solar energetic particle impacts on Earth. In doing so, I point out some intriguing correspondences as well as areas where our knowledge falls short of reaching unambiguous conclusions on, for example, the most extreme space-weather events that we can expect from the present-day Sun. The difficulties of interpreting stellar coronal light curves in terms of energetic events are illustrated with some examples provided by the SDO, STEREO, and GOES spacecraft.

Carrington cycle 24: The solar chromospheric emission in a historical and stellar perspective

K.-P. **Schroder**, M. Mittag, J.H.M.M. Schmitt, D. Jack, A. Hempelmann, J. N. Gonzalez-Perez

MNRAS **2017**

https://arxiv.org/pdf/1705.03777.pdf

We present the solar S-index record of cycle 24, obtained by the TIGRE robotic telescope facility and its high-resolution spectrograph HEROS (R≈20,000), which measures the solar chromospheric Ca II H&K line emission by using moonlight. Our calibration process uses the same set of standard stars as introduced by the Mt. Wilson team, thus giving us a direct comparison with their huge body of observations taken between 1966 and 1992, as well as with other cool stars. Carrington cycle 24 activity started from the unusually deep and long minimum 2008/09, with an S-index average of only 0.154, by 0.015 deeper than the one of 1986 ($\langle S\rangle=0.169$). In this respect,the chromospheric radiative losses differ remarkably from the variation of the coronal radio flux F10.7cm and the sunspot numbers. In addition, the cycle 24 S-amplitude remained small, 0.022 (cycles 21 and 22 averaged: 0.024), and so resulted a very low 2014 maximum of $\langle S\rangle=0.176$ (cycles 21 and 22 averaged: 0.193). We argue that this find is significant, since the Ca II H&K line emission is a good proxy for the solar far-UV flux, which plays an important role in the heating of the Earth's stratosphere, and we further argue that the solar far-UV flux changes change s with solar activity much more strongly than the total solar output.

A large-scale dataset of solar event reports from automated feature recognition modules

Michael A. **Schuh1***, Rafal A. Angryk2 and Petrus C. Martens3

J. Space Weather Space Clim., 6, A22 (**2016**)

http://www.swsc-journal.org/articles/swsc/pdf/2016/01/swsc150017.pdf

The massive repository of images of the Sun captured by the Solar Dynamics Observatory (SDO) mission has ushered in the era of Big Data for Solar Physics. In this work, we investigate the entire public collection of events reported to the Heliophysics Event Knowledgebase (HEK) from automated solar feature recognition modules operated by the SDO Feature Finding Team (FFT). With the SDO mission recently surpassing five years of

operations, and over 280,000 event reports for seven types of solar phenomena, we present the broadest and most comprehensive large-scale dataset of the SDO FFT modules to date. We also present numerous statistics on these modules, providing valuable contextual information for better understanding and validating of the individual event reports and the entire dataset as a whole. After extensive data cleaning through exploratory data analysis, we highlight several opportunities for knowledge discovery from data (KDD). Through these important prerequisite analyses presented here, the results of KDD from Solar Big Data will be overall more reliable and better understood. As the SDO mission remains operational over the coming years, these datasets will continue to grow in size and value. Future versions of this dataset will be analyzed in the general framework established in this work and maintained publicly online for easy access by the community.
See http://dmlab.cs.montana.edu/solar/

Revealing the Link Between Solar Activity and Satellite Anomalies: Career Recollections From Joe Allen,

Schultz, C.
(**2012**), Space Weather, 10, S08012,

Challenges in Specifying and Predicting Space Weather

R. W. **Schunk** , L. Scherliess , V. Eccles , L. C. Gardner, J. J. Sojka , L. Zhu , X. Pi , A. J. Mannucci , A. Komjathy , C. Wang , G. Rosen
Space Weather e2019SW002404 **Volume19, Issue2** **2021**
https://doi.org/10.1029/2019SW002404
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019SW002404
Physics-based Data Assimilation (DA) has been shown to be a powerful technique for specifying and predicting space weather. However, it is also known that different data assimilation models simulating the same geophysical event can display different space weather features even if the same data are assimilated. In this study, we used our Multimodel Ensemble Prediction System (MEPS) of DA models to elucidate the similarities and differences in the individual DA model reconstructions of the mid-low latitude ionosphere when the same data are assimilated. Ensemble model averages were also obtained. For this ensemble modeling study, we selected the quiet/storm period of **16–17 March 2013** (equinox, solar medium). Five data assimilation models and one physics-based model were used to produce an ensemble mean output for Total Electron Content (TEC), ionospheric peak density (NmF2), and ionospheric peak height (hmF2) for latitudes less than 60° and all longitudes. The data assimilated included ground-based Global Positioning Satellite TEC and topside plasma densities near 800 km altitude derived from the COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) satellites. Both a simple average and a weighted average of the models were used in the ensemble averaging in order to determine if there was an improvement of the ensemble averages over the individual models.

A New Strategy for Space Weather Specifications, Forecasts, and Science

R. W. **Schunk**, L. Scherliess, V. Eccles, L. C. Gardner, J. J. Sojka, L. Zhu, X. Pi, A. J. Mannucci, B. D. Wilson, A. Komjathy, C. Wang, and G. RosenSchunk, L. Scherliess, V. Eccles, L. C. Gardner, J. J. Sojka, L. Zhu, X. Pi, A. J. Mannucci, B. D. Wilson, A. Komjathy, C. Wang
Space Weather Quarterly, Volume 11, Issue 1, MAY **2014**
http://onlinelibrary.wiley.com/doi/10.1002/SWQv11i001/pdf

Update on the worsening particle radiation environment observed by CRaTER and implications for future human deep-space exploration†

N. A. **Schwadron**, F. Rahmanifard, J. Wilson, A. P. Jordan, H. E. Spence, C. J. Joyce, J. B. Blake, A. W. Case, W. de Wet, W. M. Farrell, J. C. Kasper, M. D. Looper, N. Lugaz, L. Mays, J. E. Mazur, J. Niehof, N. Petro, C. W. Smith, L. W. Townsend, R. Winslow, C. Zeitlin
Space Weather v. 16, no. 3, p. 289-304 **2018** **File**
http://onlinelibrary.wiley.com/doi/10.1002/2017SW001803/epdf
http://sci-hub.tw/10.1002/2017SW001803
Over the last decade, the solar wind has exhibited low densities and magnetic field strengths, representing anomalous states that have never been observed during the space age. As discussed by Schwadron et al. (2014a), the cycle 23–24 solar activity led to the longest solar minimum in more than 80 years and continued into the "mini" solar maximum of cycle 24. During this weak activity, we observed galactic cosmic ray fluxes that exceeded the levels observed throughout the space age, and we observed small solar energetic particle events. Here, we provide an update to the Schwadron et al (2014a) observations from the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) on the Lunar Reconnaissance Orbiter (LRO). The Schwadron et al. (2014a) study examined the

evolution of the interplanetary magnetic field, and utilized a previously published study by Goelzer et al. (2013) projecting out the interplanetary magnetic field strength based on the evolution of sunspots as a proxy for the rate that the Sun releases coronal mass ejections (CMEs). This led to a projection of dose rates from galactic cosmic rays on the lunar surface, which suggested a ∼20% increase of dose rates from one solar minimum to the next, and indicated that the radiation environment in space may be a worsening factor important for consideration in future planning of human space exploration. We compare the predictions of Schwadron et al. (2014a) with the actual dose rates observed by CRaTER in the last 4 years. The observed dose rates exceed the predictions by ∼10%, showing that the radiation environment is worsening more rapidly than previously estimated. Much of this increase is attributable to relatively low-energy ions, which can be effectively shielded. Despite the continued paucity of solar activity, one of the hardest solar events in almost a decade occurred in Sept 2017 after more than a year of all-clear periods. These particle radiation conditions present important issues that must be carefully studied and accounted for in the planning and design of future missions (to the Moon, Mars, asteroids and beyond).

5. Successive CMEs in Development of the September 2017 SEP events

Particle Radiation Sources, Propagation and Interactions in Deep Space, at Earth, the Moon, Mars, and Beyond: Examples of Radiation Interactions and Effects **Review**

Schwadron, N.A., Cooper, J.F., Desai, M. et al.

Space Sci Rev Volume 212, Issue 3–4, pp 1069–1106 (**2017**). doi:10.1007/s11214-017-0381-5

Part of the following topical collections:

The Scientific Foundation of Space Weather

https://link.springer.com/content/pdf/10.1007%2Fs11214-017-0381-5.pdf

Particle radiation has significant effects for astronauts, satellites and planetary bodies throughout the Solar System. Acute space radiation hazards pose risks to human and robotic exploration. This radiation also naturally weathers the exposed surface regolith of the Moon, the two moons of Mars, and other airless bodies, and contributes to chemical evolution of planetary atmospheres at Earth, Mars, Venus, Titan, and Pluto. We provide a select review of recent areas of research covering the origin of SEPs from coronal mass ejections low in the corona, propagation of events through the solar system during the anomalously weak solar cycle 24 and important examples of radiation interactions for Earth, other planets and airless bodies such as the Moon.

Does the worsening galactic cosmic radiation environment observed by CRaTER preclude future manned deep space exploration?

N. A. **Schwadron**, J. B. Blake, A. W. Case, C. J. Joyce, J. Kasper, J. Mazur, N. Petro, M. Quinn, J. A. Porter, C. W. Smith, S. Smith, H. E. Spence, L. W. Townsend, R. Turner, J. K. Wilson and C. Zeitlin

Space Weather, Volume 12, Issue 11, pages 622–632, November **2014**

Space Weather Quarterly Vol. 12, Issue 1, **2015**

The Sun and its solar wind are currently exhibiting extremely low densities and magnetic field strengths, representing states that have never been observed during the space age. The highly abnormal solar activity between cycles 23 and 24 has caused the longest solar minimum in over 80 years and continues into the unusually small solar maximum of cycle 24. As a result of the remarkably weak solar activity, we have also observed the highest fluxes of galactic cosmic rays in the space age and relatively small solar energetic particle events. We use observations from the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) on the Lunar Reconnaissance Orbiter to examine the implications of these highly unusual solar conditions for human space exploration. We show that while these conditions are not a show stopper for long-duration missions (e.g., to the Moon, an asteroid, or Mars), galactic cosmic ray radiation remains a significant and worsening factor that limits mission durations. While solar energetic particle events in cycle 24 present some hazard, the accumulated doses for astronauts behind 10 g/cm^2 shielding are well below current dose limits. Galactic cosmic radiation presents a more significant challenge: the time to 3% risk of exposure-induced death (REID) in interplanetary space was less than 400 days for a 30 year old male and less than 300 days for a 30 year old female in the last cycle 23–24 minimum. The time to 3% REID is estimated to be ∼20% lower in the coming cycle 24–25 minimum. If the heliospheric magnetic field continues to weaken over time, as is likely, then allowable mission durations will decrease correspondingly. Thus, we estimate exposures in extreme solar minimum conditions and the corresponding effects on allowable durations.

Earth-Moon-Mars Radiation Environment Module framework

Schwadron, N. A.; Townsend, L.; Kozarev, K.; Dayeh, M. A.; Cucinotta, F.; Desai, M.; Golightly, M.; Hassler, D.; Hatcher, R.; Kim, M.-Y.; Posner, A.; PourArsalan, M.; Spence, H. E.; Squier, R. K.

Space Weather, Vol. 8, No. 1, S00E02, **2010**

http://dx.doi.org/10.1029/2009SW000523

We are preparing to return humans to the Moon and setting the stage for exploration to Mars and beyond. However, it is unclear if long missions outside of low-Earth orbit can be accomplished with acceptable risk. The central objective of a new modeling project, the Earth-Moon-Mars Radiation Exposure Module (EMMREM), is to develop and validate a numerical module for characterizing time-dependent radiation exposure in the Earth-Moon-Mars and interplanetary space environments. EMMREM is being designed for broad use by researchers to predict radiation exposure by integrating over almost any incident particle distribution from interplanetary space. We detail here the overall structure of the EMMREM module and study the dose histories of the 2003 Halloween storm event and a June 2004 event. We show both the event histories measured at 1 AU and the evolution of these events at observer locations beyond 1 AU. The results are compared to observations at Ulysses. The model allows us to predict how the radiation environment evolves with radial distance from the Sun. The model comparison also suggests areas in which our understanding of the physics of particle propagation and energization needs to be improved to better forecast the radiation environment. Thus, we introduce the suite of EMMREM tools, which will be used to improve risk assessment models so that future human exploration missions can be adequately planned for.

Space Weather: The Solar Perspective

Rainer **Schwenn**

Living Rev. Solar Phys., 3, (**2006**), 2; **File**

The term space weather refers to conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and that can affect human life and health. Our modern hi-tech society has become increasingly vulnerable to disturbances from outside the Earth system, in particular to those initiated by explosive events on the Sun: Flares release flashes of radiation that can heat up the terrestrial atmosphere such that satellites are slowed down and drop into lower orbits, solar energetic particles accelerated to near-relativistic energies may endanger astronauts traveling through interplanetary space, and coronal mass ejections are gigantic clouds of ionized gas ejected into interplanetary space that after a few hours or days may hit the Earth and cause geomagnetic storms. In this review, I describe the several chains of actions originating in our parent star, the Sun, that affect Earth, with particular attention to the solar phenomena and the subsequent effects in interplanetary space.

Halo Coronal Mass Ejections during Solar Cycle 24: reconstruction of the global scenario and geoeffectiveness

Camilla **Scolini**, Mauro Messerotti, Stefaan Poedts, Luciano Rodriguez

Journal of Space Weather and Space Climate 2017

https://arxiv.org/pdf/1712.05847.pdf **File**

In this study we present a statistical analysis of 53 fast Earth-directed halo CMEs observed by the SOHO/LASCO instrument during the period Jan. 2009-Sep. 2015, and we use this CME sample to test the capabilities of a Sun-to-Earth prediction scheme for CME geoeffectiveness. First, we investigate the CME association with other solar activity features by means of multi-instrument observations of the solar magnetic and plasma properties. Second, using coronagraphic images to derive the CME kinematical properties at 0.1 AU, we propagate the events to 1 AU by means of the WSA-ENLIL+Cone model. Simulation results at Earth are compared with in-situ observations at L1. By applying the pressure balance condition at the magnetopause and a solar wind-Kp index coupling function, we estimate the expected magnetospheric compression and geomagnetic activity level, and compare them with global data records. The analysis indicates that 82% of the CMEs arrived at Earth in the next 4 days. Almost the totality of them compressed the magnetopause below geosynchronous orbits and triggered a geomagnetic storm. Complex sunspot-rich active regions associated with energetic flares result the most favourable configurations from which geoeffective CMEs originate. The analysis of related SEP events shows that 74% of the CMEs associated with major SEPs were geoeffective. Moreover, the SEP production is enhanced in the case of fast and interacting CMEs. In this work we present a first attempt at applying a Sun-to-Earth geoeffectiveness prediction scheme - based on 3D simulations and solar wind-geomagnetic activity coupling functions - to a statistical set of potentially geoeffective halo CMEs. The results of the prediction scheme are in good agreement with geomagnetic activity data records, although further studies performing a fine-tuning of such scheme are needed. **5-13 March 2012, 18-27 June 2015**,

Table 1. Complete list of the selected CME events.

Space Weather Prediction from the Ground: Case of CHAIN

Daikichi **Seki**, Satoru Ueno, Hiroaki Isobe, Kenichi Otsuji, Denis P. Cabezas, Kiyoshi Ichimoto, Kazunari Shibata, CHAIN team

Sun and Geosphere 13/2: 157 2018

https://arxiv.org/ftp/arxiv/papers/1808/1808.06295.pdf

http://newserver.stil.bas.bg/SUNGEO//00SGArhiv/SG_v13_No2_2018-pp-157-161.pdf

In this article, we insist on the importance and the challenges of the prediction of solar eruptive phenomena including flares, coronal mass ejections (CME), and filament eruptions fully based on the ground-based telescopes. It is true that satellites' data are indispensable for the space weather prediction, but they are vulnerable to the space weather effects. Therefore, the ground-based telescopes can be complementary to them from the viewpoint of space weather prediction. From this view point, one possible new flare prediction method that makes use of H-alpha, red wings, and blue wings images obtained by the SDDI/SMART, the ground-based telescope at Hida Observatory, is presented. And in order to show the possibility for the actual operation based on that method, the recent progress of CHAIN project, the international observation network, is mentioned in terms of their outcomes and capacity buildings. **2016 November 5**

Kp forecasting with a recurrent neural network

Ernest Scott **Sexton**, Katariina Nykyri and Xuanye Ma

J. Space Weather Space Clim. **2019**, 9, A19

https://www.swsc-journal.org/articles/swsc/pdf/2019/01/swsc180037.pdf

In an effort to forecast the planetary Kp-index beyond the current 1-hour and 4-hour predictions, a recurrent neural network is trained on three decades of historical data from NASA's Omni virtual observatory and forecasts Kp with a prediction horizon of up to 24 h. Using Matlab's neural network toolbox, the multilayer perceptron model is trained on inputs comprised of Kp for a given time step as well as from different sets of the following six solar wind parameters, Bz, n, V, |B|, σB and σ_{B_z}. The purpose of this study was to test which combination of the solar wind and Interplanetary Magnetic Field (IMF) parameters used for training gives the best performance as defined by correlation coefficient, C, between the predicted and actually measured Kp values and Root Mean Square Error (RMSE). The model consists of an input layer, a single nonlinear hidden layer with 28 neurons, and a linear output layer that predicts Kp up to 24 h in advance. For 24 h prediction, the network trained on Bz, n, V, |B|, σB performs the best giving C in the range from 0.8189 (for 31 predictions) to 0.8211 (for 9 months of predictions), with the smallest RMSE.

Chapter 6 - Data-Driven Modeling of Extreme Space Weather

A. Surjalal **Sharma**

In: Extreme Events in Geospace

Origins, Predictability, and Consequences **Book**

Editor: Natalia **Buzulukova**, Elsevier, **2018**, 798 p. **File**

Pages 139-153

http://sci-hub.se/10.1016/B978-0-12-812700-1.00006-6

Data-driven modeling based on complexity science is a framework for the modeling and prediction of extreme events and for quantifying the associated predictability. The dynamical features derived from the time series data of space weather, from ground-based and spacecraft-borne instruments, yield predictions of the typical behavior; the large deviations from it are the extreme events. An underlying feature of extreme events is the long-range correlations in the system; this is characterized by scaling exponents, such as Hurst exponents. Computations of these exponents require removal of trends in the data to avoid spurious correlations and in these studies the detrended fluctuation analysis is used. The exponents computed after trend removal provide a measure of the long-range correlation in space weather and thus a means to quantify the predictability. The data-driven modeling of space weather, based on the dynamical systems theory, thus yields predictions based on the dynamical features and the likelihood of extreme events based on the intrinsic nature of the fluctuations.

Predictive capability for extreme space weather events,

Sharma, A. S., E. E. Kalnay, and M. Bonadonna

Eos, 98, https://doi.org/10.1029/2017EO071721. Published on 26 April **2017**.

Workshop on Modeling and Prediction of Extreme Space Weather Events; College Park, Maryland, 22–24 August 2016.

Verification of Space Weather Forecasts Issued by the Met Office Space Weather Operations Centre

M. A. **Sharpe**, S. A. Murray

Space Weather Volume 15, Issue 10 October **2017** Pages 1383–1395

http://sci-hub.cc/10.1002/2017SW001683

The Met Office Space Weather Operations Centre was founded in 2014 and part of its remit is a daily Space Weather Technical Forecast to help the UK build resilience to space weather impacts; guidance includes 4 day geomagnetic storm forecasts (GMSF) and X-ray flare forecasts (XRFF). It is crucial for forecasters, users, modelers, and stakeholders to understand the strengths and weaknesses of these forecasts; therefore, it is important to verify against the most reliable truth data source available. The present study contains verification results for XRFFs using

Geo-Orbiting Earth Satellite 15 satellite data and GMSF using planetary K-index (Kp) values from the GFZ Helmholtz Centre. To assess the value of the verification results, it is helpful to compare them against a reference forecast and the frequency of occurrence during a rolling prediction period is used for this purpose. An analysis of the rolling 12 month performance over a 19 month period suggests that both the XRFF and GMSF struggle to provide a better prediction than the reference. However, a relative operating characteristic and reliability analysis of the full 19 month period reveals that although the GMSF and XRFF possess discriminatory skill, events tend to be overforecast.

Space Weather and the Ground-Level Solar Proton Events of the 23rd Solar Cycle

Shea, M. A.; Smart, D. F. **Review**

Space Sci. Rev., 171, Numbers 1-4, 161-188, **2012, File**

Solar proton events can adversely affect space and ground-based systems. Ground-level events are a subset of solar proton events that have a harder spectrum than average solar proton events and are detectable on Earth's surface by cosmic radiation ionization chambers, muon detectors, and neutron monitors. This paper summarizes the space weather effects associated with ground-level solar proton events during the 23rd solar cycle. These effects include communication and navigation systems, spacecraft electronics and operations, space power systems, manned space missions, and commercial aircraft operations. The major effect of ground-level events that affect manned spacecraft operations is increased radiation exposure. The primary effect on commercial aircraft operations is the loss of high frequency communication and, at extreme polar latitudes, an increase in the radiation exposure above that experienced from the background galactic cosmic radiation. Calculations of the maximum potential aircraft polar route exposure for each ground-level event of the 23rd solar cycle are presented. The space weather effects in October and November 2003 are highlighted together with on-going efforts to utilize cosmic ray neutron monitors to predict high energy solar proton events, thus providing an alert so that system operators can possibly make adjustments to vulnerable spacecraft operations and polar aircraft routes.

Effects of Nearly Frontal and Highly Inclined Interplanetary Shocks on High-Latitude Field-Aligned Currents (FACs)

Yining **Shi**, Denny M. Oliveira, Delores J. Knipp, Eftyhia Zesta, Tomoko Matsuo, Brian Anderson

Space Weather **2019**

https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2019SW002367

We present high-latitude field-aligned current (FAC) response to nearly frontal shocks (NFSs) and highly inclined shocks (HISs) through a superposed epoch analysis. The FACs are derived from magnetic perturbation data provided by the Active Magnetosphere and Planetary Electrodynamics Response Experiment program. Forty-nine events for each group are used for the superposed epoch analysis. The 25%, 50%, and 75% quantiles of the FAC and total current distributions are studied. We found that NFSs are statistically stronger shocks in terms of solar wind parameters such as solar wind speed and interplanetary magnetic field.For the 50% quantiles, both groups of shocks produce rapid increases in total currents after shock arrival, but NFSs result in sharper increase in FACs and more intense FACs compared to HISs. At the 50% and 75% quantiles, NFSs trigger stronger auroral-zone current disturbance for the first hour after shock arrival than do HISs. Spatially, the difference in FAC response is most notable in (1) the dayside noon region, (2) the duskside Region 2 current system, and (3) the dawnside prenoon Region 1 current system. Our results are consistent with previous numerical simulations that showed more symmetric and stronger compression of the magnetosphere for high-speed and nearly frontal shocks. We observationally confirm the role of shock impact angle in controlling the subsequent shock geoeffectiveness for fast shocks. We assert that determining the shock impact angle via an upstream solar wind model could provide useful insight in forecasting the geoeffectiveness of a shock prior to its arrival at the magnetopause.

Inner heliosphere MHD modeling system applicable to space weather forecasting for the other planets

D. **Shiota**1, R. Kataoka2, Y. Miyoshi1, T. Hara1, C. Tao3,4, K. Masunaga5,6, Y. Futaana6 and N. Terada

Space Weathe, Volume 12, Issue 4, pages 187–204, April **2014**

We developed a magnetohydrodynamic (MHD) solar wind model which can be used for practical use in real-time space weather forecasting at Earth's orbit and those of other planets. The MHD simulation covering 3 years (2007–2009) was performed to test the accuracy, and the numerical results show reasonable agreement with in situ measurements of the solar wind at Earth's orbit and with measurements at Venus and Mars by Venus Express and Mars Express, respectively. The comparison also shows that the numerical results can be used to detect stream interfaces, which is useful for space weather forecast of killer electrons in the outer Van Allen belt.

A Machine-Learning-Ready Dataset Prepared from the Solar and Heliospheric Observatory Mission

Carl **Shneider** (1), Andong Hu (1), Ajay K. Tiwari (1), Monica G. Bobra (2), Karl Battams (5), Jannis Teunissen (1), Enrico Camporeale
2021
https://arxiv.org/pdf/2108.06394.pdf
We present a Python tool to generate a standard dataset from solar images that allows for user-defined selection criteria and a range of pre-processing steps. Our Python tool works with all image products from both the Solar and Heliospheric Observatory (SoHO) and Solar Dynamics Observatory (SDO) missions. We discuss a dataset produced from the SoHO mission's multi-spectral images which is free of missing or corrupt data as well as planetary transits in coronagraph images, and is temporally synced making it ready for input to a machine learning system. Machine-learning-ready images are a valuable resource for the community because they can be used, for example, for forecasting space weather parameters. We illustrate the use of this data with a 3-5 day-ahead forecast of the north-south component of the interplanetary magnetic field (IMF) observed at Lagrange point one (L1). For this use case, we apply a deep convolutional neural network (CNN) to a subset of the full SoHO dataset and compare with baseline results from a Gaussian Naive Bayes classifier.

An Interview With Dan Baker on NRC's Space Weather Strategy,
Showstack, R.
Space Weather, 10, (**2012**), S11006, doi:10.1029/2012SW000877.
http://www.agu.org/journals/sw/swa/news/article/?id=2012SW000877
The U.S. National Research Council's (NRC)report Solar and Space Physics: A Science for a Technological Society, which was released on 15 August, is a decadal strategy that includes overarching goals and key recommendations for basic and applied research in solar and space physics for **2013-2022**.

Space Weather Enterprise Forum Includes Broad Range of Discussion,
Showstack, R.
(**2012**), Space Weather, 10, S08013,
With the 2013 solar maximum nearing, researchers and government agencies are focusing on how the increased solar activity could affect our increasingly technological society and what measures can be taken to help prevent or mitigate any threats to the electricity grid, GPS, and other potentially vulnerable technological soft spots.
For more information, see http://www.ofcm.noaa.gov/swef/2012/index-swef2012.htm

Nowcasting and Predicting the Kp Index Using Historical Values and Real-Time Observations
Yuri Y. **Shprits** , Ruggero Vasile , Irina S. Zhelavskaya
Volume17, Issue8 August **2019** Pages 1219-1229
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2018SW002141
sci-hub.se/10.1029/2018SW002141
Current algorithms for the real-time prediction of the Kp index use a combination of models empirically driven by solar wind measurements at the L1 Lagrange point and historical values of the index. In this study, we explore the limitations of this approach, examining the forecast for short and long lead times using measurements at L1 and Kp time series as input to artificial neural networks. We explore the relative efficiency of the solar wind-based predictions, predictions based on recurrence, and predictions based on persistence. Our modeling results show that for short-term forecasts of approximately half a day, the addition of the historical values of Kp to the measured solar wind values provides a barely noticeable improvement. For a longer-term forecast of more than 2 days, predictions can be made using recurrence only, while solar wind measurements provide very little improvement for a forecast with long horizon times. We also examine predictions for disturbed and quiet geomagnetic activity conditions. Our results show that the paucity of historical measurements of the solar wind for high Kp results in a lower accuracy of predictions during disturbed conditions. Rebalancing of input data can help tailor the predictions for more disturbed conditions.

Hierarchical approach to forecasting recurrent solar wind streams
Yu. S**. Shugay**, I. S. Veselovsky, D. B. Seaton and D. Berghmans
Solar System Research, Volume 45, Number 6, 546-556, **2011**
Astronomicheskii Vestnik, **2011**, Vol. 45, No. 6, pp. 560–571.
The hierarchical approach to predicting quasi-stationary, high-speed solar wind (SW) streams is described. This approach integrates various types of data into a single forecasting system by means of an ensemble of experts. The input data included the daily values of the coronal hole areas, which were calculated from the ultraviolet images of the Sun, and the speed of the SW streams during the previous solar rotations. The coronal hole areas were calculated from the images taken by the SWAP instrument aboard the PROBA2 satellite in the spectral interval centered at a

wavelength of 17.4 nm and by the AIA instrument aboard the SDO spacecraft in the interval of wavelengths centered at 19.3 and 17.1 nm. The forecast was based on the data for 2010, corresponding to the rising phase of the 24th solar cycle. On the first hierarchical level, a few simple model estimates were obtained for the speed of the SW streams from the input data of each type. On the second level of hierarchy, the final 3 day ahead forecast of the SW velocity was formulated on the basis of the obtained estimates. The proposed hierarchical approach improves the accuracy of forecasting the SW velocity. In addition, in such a method of prediction, the data gaps in the records of one instrument do not crucially affect the final result of forecasting of the system as a whole.

Rieger-type periodicities on the Sun and the Earth during solar cycles 21 and 22

H. G. **Silva**, I. Lopes

Astrophysics and Space Science March **2017**, 362:44 DOI: 10.1007/s10509-017-3020-4

Rieger-type periods of the magnetic sunspot area time series have been found in two atmospheric time-series variables: neutron monitor count rate and atmospheric electric potential gradient. The data considered comprises two solar cycles (21, 22) and spans from 1978 to 1990. The study reveals the existence of similar and correlated features in sunspot area as well as neutron counts and atmospheric electric potential gradient, favoring the possibility that the Sun's activity affects the Earth's atmosphere and weather at a time scale between 150–300 days. Moreover, five different Rieger-type periods in the sunspot area time series are found, four of which are detected in the neutron monitor count rate, and three in the atmospheric electric potential gradient. These values are consistent with the periods predicted for stationary solar Rossby waves existing inside the Sun. The possibility is discussed that instabilities on the solar magnetic field caused by solar Rossby waves in the Sun's interior might indirectly be affecting the activity of the heliosphere and the Earth's atmosphere.

Nowcasting and validating Earth's electric-field response to extreme space-weather events using magnetotelluric data: application to the September 2017 geomagnetic storm and comparison to observed and modelled fields in Scotland

Fiona **Simpson**, Karsten Bahr

Space Weather **2020**

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019SW002432

In the UK, geomagnetically induced currents (GICs) are calculated from thin-sheet electrical conductivity models. In the absence of conductivity models, time derivatives of magnetic fields are sometimes used as proxies for GIC-related electric fields. An alternative approach, favored in the US, is to calculate storm-time electric fields from time-independent impedance tensors computed from an array of magnetotelluric (MT) sites and storm-time magnetic fields recorded at geomagnetic observatories or assumed from line-current models. A paucity of direct measurements of storm-time electric fields has restricted validation of these different techniques for nowcasting electric fields and GICs. Here, we present unique storm-time electric-field data from 7 MT sites in Scotland that recorded before, during and after the **September 2017** magnetic storm. By Fourier transforming electric-field spectra computed using different techniques back to the time domain, we are able to make direct comparisons with these measured storm-time electric-field time series. This enables us to test the validity of different approaches to nowcasting electric fields. Our preferred technique involves frequency-domain multiplication of magnetic-field spectra from a regional site with a local impedance tensor that has been corrected for horizontal magnetic-field gradients present between the local site and the regional site using perturbation tensors derived from geomagnetic depth sounding (GDS). Scatter plots of scaling factors between measured and nowcasted electric fields demonstrate the importance of coupling between the polarization of the storm-time magnetic source field and Earth's direction-dependent deep electrical conductivity structure.

In situ observations from STEREO/PLASTIC: a test for L5 space weather monitors

K. D. C. **Simunac**, L. M. Kistler, A. B. Galvin, M. A. Popecki, and C. J. Farrugia

Ann. Geophys., 27, 3805-3809, **2009**

Abstract Full Article (PDF, 1634 KB)

Stream interaction regions (SIRs) that corotate with the Sun (corotating interaction regions, or CIRs) are known to cause recurrent geomagnetic storms. The Earth's L5 Lagrange point, separated from the Earth by 60 degrees in heliographic longitude, is a logical location for a solar wind monitor – nearly all SIRs/CIRs will be observed at L5 several days prior to their arrival at Earth. Because the Sun's heliographic equator is tilted about 7 degrees with respect to the ecliptic plane, the separation in heliographic latitude between L5 and Earth can be more than 5 degrees. In July 2008, during the period of minimal solar activity at the end of solar cycle 23, the two STEREO observatories were separated by about 60 degrees in longitude and more than 4 degrees in heliographic latitude. This time period affords a timely test for the practical application of a solar wind monitor at L5. We compare in situ observations from PLASTIC/AHEAD and PLASTIC/BEHIND, and report on how well the BEHIND data can be used as a forecasting tool for in situ conditions at the AHEAD spacecraft with the assumptions of ideal corotation and minimal source evolution. Preliminary results show the bulk proton parameters (density and bulk speed) are not in quantitative agreement from one observatory to the next, but the qualitative profiles are similar.

A Modified Spheromak Model Suitable for Coronal Mass Ejection Simulations

Talwinder **Singh**, Mehmet S. Yalim, Nikolai V. Pogorelov, Nat Gopalswamy
2020
https://arxiv.org/pdf/2002.10409.pdf **File**

Coronal Mass Ejections (CMEs) are one of the primary drivers of extreme space weather. They are large eruptions of mass and magnetic field from the solar corona and can travel the distance between Sun and Earth in half a day to a few days. Predictions of CMEs at 1 Astronomical Unit (AU), in terms of both its arrival time and magnetic field configuration, are very important for predicting space weather. Magnetohydrodynamic (MHD) modeling of CMEs, using flux-rope-based models is a promising tool for achieving this goal. In this study, we present one such model for CME simulations, based on spheromak magnetic field configuration. We have modified the spheromak solution to allow for independent input of poloidal and toroidal fluxes. The motivation for this is a possibility to estimate these fluxes from solar magnetograms and extreme ultraviolet (EUV) data from a number of different approaches. We estimate the poloidal flux of CME using post eruption arcades (PEAs) and toroidal flux from the coronal dimming. In this modified spheromak, we also have an option to control the helicity sign of flux ropes, which can be derived from the solar disk magnetograms using the magnetic tongue approach. We demonstate the applicability of this model by simulating the **12 July 2012** CME in the solar corona.

PreMevE Update: Forecasting Ultra-Relativistic Electrons Inside Earth's Outer Radiation Belt

Saurabh **Sinha**, Yue Chen, Youzuo Lin, Rafael Pires de Lima
Space Weather Volume19, Issue9 e2021SW002773 **2021**
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https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021SW002773

Energetic electrons inside Earth's Van Allen belts pose a major radiation threat to space-borne electronics that often play vital roles in modern society. Ultra-relativistic electrons with energies greater than or equal to two megaelectron-volt (MeV) are of particular interest, and thus forecasting these ≥2 MeV electrons has a significant meaning to all space sectors. Here, we update the latest development of the predictive model for MeV electrons in the outer radiation belt. The new version, called PREdictive MEV Electron (PreMevE)-2E, forecasts ultra-relativistic electron flux distributions across the outer belt, with no need for in situ measurements of the trapped MeV electron population except at the geosynchronous orbit (GEO). Model inputs include precipitating electrons observed in low-Earth-orbits by NOAA satellites, upstream solar wind speeds and densities from solar wind monitors, as well as ultra-relativistic electrons measured by one Los Alamos GEO satellite. We evaluated 32 supervised machine learning models that fall into four different classes of linear and neural network architectures, and successfully tested ensemble forecasting by using groups of top-performing models. All models are individually trained, validated, and tested by in situ electron data from NASA's Van Allen Probes mission. It is shown that the final ensemble model outperforms individual models at most L-shells, and this PreMevE-2E model can provide 25-h (~1-day) and 50-h (~2-day) forecasts with high mean performance efficiency and correlation values. Our results also suggest that this new model is dominated by nonlinear components at L-shells <~4 for ultra-relativistic electrons, different from the dominance of linear components for 1 MeV electrons as previously discovered.

Chapter 11 - Empirical Modeling of Extreme Events: Storm-Time Geomagnetic Field, Electric Current, and Pressure Distributions **Review**

Mikhail I.**Sitnov**⁎Grant K.Stephens⁎MatinaGkioulidou⁎ViacheslavMerkin⁎Aleksandr Y.Ukhorskiy⁎HajeKorth⁎Pontus C.Brandt⁎Nikolai A.Tsyganenko†
In: Extreme Events in Geospace Origins, Predictability, and Consequences **2018**, Pages 259-279
http://sci-hub.tw/10.1016/B978-0-12-812700-1.00011-X

Recent advances in empirical modeling of the magnetospheric magnetic field and underlying electric currents, including reconstruction of the eastward current, make it possible to derive the distribution of the force-free isotropic storm-time plasma pressure. Here we consider such distributions for two extreme events, the July 2000 (Bastille Day) storm with Sym−Hmin ≃−300 nT and the March 2015 event, the strongest storm in the Van Allen Probes era with Sym−Hmin ≃−200 nT. We find that the main phase pressure distributions are strongly localized in radius and limited in local time with pressure peaking in the premidnight sector. More azimuthally symmetric distributions in the early main phase and in the recovery phase may still have pressure enhancements on the dayside and in the postmidnight sector. The degree of possible underestimation of current and pressure values in empirical modeling of extreme events is evaluated and attributed to limited representation of such events in historical records. A method of the model renormalization to mitigate this problem is described.

The Badhwar-O'Neill 2020 GCR Model

T.C. **Slaba** , K. Whitman
Space Weather **Volume18, Issue6** e2020SW002456 **2020**
https://doi.org/10.1029/2020SW002456
https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020SW002456
The Badhwar-O'Neill (BON) model has been used for some time to describe the galactic cosmic ray (GCR) environment encountered in deep space by astronauts and sensitive electronics. The most recent version of the model, BON2014, was calibrated to available measurements to reduce model errors for particles and energies of significance to astronaut exposure. Although subsequent studies showed the model to be reasonably accurate for such applications, modifications to the sunspot number (SSN) classification system and a large number of new high-precision measurements suggested the need to develop an improved and more capable model. In this work, the BON2020 model is described. The new model relies on daily integral flux from the Advanced Composition Explorer Cosmic Ray Isotope Spectrometer (ACE/CRIS) to describe solar activity. For time periods not covered by ACE/CRIS, the updated international SSN database is used. Parameters in the new model are calibrated to available data, which includes the new Alpha Magnetic Spectrometer (AMS-02) and Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) high-precision measurements. It is found that the BON2020 model is a significant improvement over BON2014. Systematic bias associated with BON2014 have been removed. The average relative error of the BON2020 model compared to all available measurements is found to be <1%, and BON2020 is found to be within +15% of a large fraction of the available measurements (26,269 of 27,646 → 95%).

Space Weather Forecasts of Ground Level Space Weather in the UK: Evaluating Performance and Limitations

A. W. **Smith**, I. J. Rae, C. Forsyth, J. C. Coxon, M.-T. Walach, C. J. Lao, D. S. Bloomfield, S. A. Reddy, M. K. Coughlan, A. Keesee, S. Bentley
Space Weather Volume22, Issue11 November **2024** e2024SW003973
https://doi.org/10.1029/2024SW003973
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2024SW003973
Geomagnetically Induced Currents (GICs) are a severe space weather hazard, driven through coupling between the solar wind and magnetosphere. GICs are rarely measured directly, instead the ground magnetic field variability is often used as a proxy. Recently space weather models have been developed to forecast whether the magnetic field variability (R) will exceed specific, extreme thresholds. We test an example machine learning-based model developed for the northern United Kingdom. We evaluate its performance (discriminative skill and calibration) as a function of magnetospheric state, solar wind input and magnetic local time. We find that the model's performance is highest during active conditions, for example, geomagnetic storms, and lowest during isolated substorms and "quiet" intervals, despite these conditions dominating the training data set. Correspondingly, the performance is high when the solar wind conditions are elevated (i.e., high velocity, large total magnetic field strength, and the interplanetary magnetic field oriented southward), and at a minimum when the north-south component of the magnetic field is highly variable or around zero. Regarding magnetic local time, performance is highest within the dusk and night sectors, and lowest during the day. The model appears to capture multiple modes of magnetospheric activity, including substorms and viscous interactions, but poorly predicts impulsive phenomena (i.e., storm sudden commencements) and longer timescale coupling processes. Future models of mid-latitude magnetic field variability will need to effectively use longer time intervals of unpropagated (i.e., observations from L1) solar wind to more completely describe the magnetospheric conditions and response.

The heliospheric magnetic flux, solar wind proton flux, and cosmic ray intensity during the coming solar minimum

Charles W. **Smith**1,2, K. G. McCracken3, Nathan A. Schwadron1,2 andMolly L. Goelzer
Space Weather, Volume 12, Issue 7, pages 499–507, July **2014**
Recent papers have linked the heliospheric magnetic flux to the sunspot cycle with good correlation observed between prediction and observation. Other papers have shown a strong correlation between magnetic flux and solar wind proton flux from coronal holes. We combine these efforts with an expectation that the sunspot activity of the approaching solar minimum will resemble the Dalton or Gleissberg Minimum and predict that the magnetic flux and solar wind proton flux over the coming decade will be lower than at any time during the space age. Using these predictions and established theory, we also predict record high galactic cosmic ray intensities over the same years. The analysis shown here is a prediction of global space climate change within which space weather operates. It predicts a new parameter regime for the transient space weather behavior that can be expected during the coming decade.

The Natural Changes of Solar-Terrestrial Relations

G.Y. **Smolkov**
Advances in Astrophysics, Vol. 3, No. 4, November **2018**, p. 205-216

http://www.isaacpub.org/images/PaperPDF/AdAp_100092_2018101911200904145.pdf
Natural changes in solar-terrestrial relations, including the global climate of the Earth, without taking into account all the factors of external influence on them, are still completely incomprehensible. In this connection, synchronous responses of the atmosphere layers of the Sun and all shells of the Earth, due to external influences on them in 1997-1998 were considered. The events and processes of these years have caused a temporary slowdown in global warming in 1998-2013.

Locations Where Space Weather Energy Impacts the Atmosphere **Review**

Jan J. **Sojka**

Space Sci Rev Volume 212, Issue 3–4, pp 1041–1067 (**2017**). doi:10.1007/s11214-017-0379-z

https://link.springer.com/content/pdf/10.1007%2Fs11214-017-0379-z.pdf

In this review we consider aspects of space weather that can have a severe impact on the terrestrial atmosphere. We begin by identifying the pre-conditioning role of the Sun on the temperature and density of the upper atmosphere. This effect we define as “space climatology”. Space weather effects are then defined as severe departures from this state of the atmospheric energy and density. Three specific forms of space weather are reviewed and we show that each generates severe space weather impacts. The three forms of space weather being considered are the solar photon flux (flares), particle precipitation (aurora), and electromagnetic Joule heating (magnetosphere–ionospheric (M-I) coupling).

We provide an overview of the physical processes associated with each of these space weather forms. In each case a very specific altitude range exists over which the processes can most effectively impact the atmosphere. Our argument is that a severe change in the local atmosphere’s state leads to atmospheric heating and other dynamic changes at locations beyond the input heat source region. All three space weather forms have their greatest atmospheric impact between 100 and 130 km. This altitude region comprises the transition between the atmosphere’s mesosphere and thermosphere and is the ionosphere’s E-region. This region is commonly referred to as the Space Atmosphere Interaction Region (SAIR). The SAIR also acts to insulate the lower atmosphere from the space weather impact of energy deposition. A similar space weather zone would be present in atmospheres of other planets and exoplanets.

Algorithm for Analysis of Power Grid Vulnerability to Geomagnetic Disturbances

O. **Sokolova** , P. Burgherr , Ya. Sakharov , N. Korovkin

Space Weather **2018**

sci-hub.tw/10.1029/2018SW001931

Multiple power system equipment damage from strong geomagnetic disturbance (GMD) can significantly disrupt power grid operation. This has happened twice: in 1989, in North America and the United Kingdom and, in 2003, in Scandinavia and South Africa. Modern bulk high-voltage power grids were designed more than 60 years ago for achieving more economic benefits in power transfer. In turn, high-voltage, and especially the lately designed ultrahigh-voltage, grids are more vulnerable to GMD. It is anticipated that the demand of detailed study of power grid's vulnerability to GMD will expand with broader awareness of the negative effects. The common approach requires the knowledge of the data on geophysical parameters of the study region, which is not accessible to the specialists without relevant background. In this paper, an alternative algorithm for preliminary evaluation of power grid's robustness to GMD is proposed. It takes into account various critical factors and provides a useful tool for stakeholders to identify potentially weak power grids and develop mitigation procedures beforehand. The advantage is that this algorithm can be used by specialists who do not have a comprehensive understanding of the GMD effect on power grid operation.

Optimizing the real-time ground level enhancement alert system based on neutron monitor measurements: Introducing GLE Alert Plus

G. **Souvatzoglou**, A. Papaioannou, H. Mavromichalaki, J. Dimitroulakos and C. Sarlanis

Space Weather, Volume 12, Issue 11, pages 633–649, November **2014**

sci-hub.se/10.1002/2014SW001102

Whenever a significant intensity increase is being recorded by at least three neutron monitor stations in real-time mode, a ground level enhancement (GLE) event is marked and an automated alert is issued. Although, the physical concept of the algorithm is solid and has efficiently worked in a number of cases, the availability of real-time data is still an open issue and makes timely GLE alerts quite challenging. In this work we present the optimization of the GLE alert that has been set into operation since 2006 at the Athens Neutron Monitor Station. This upgrade has led to *GLE Alert Plus*, which is currently based upon the Neutron Monitor Database (NMDB). We have determined the critical values per station allowing us to issue reliable GLE alerts close to the initiation of the event while at the same time we keep the false alert rate at low levels. Furthermore, we have managed to treat the problem of data availability, introducing the Go-Back-N algorithm. A total of 13 GLE events have been marked from January 2000 to December 2012. *GLE Alert Plus* issued an alert for 12 events. These alert times are compared to the alert times of GOES Space Weather Prediction Center and Solar Energetic Particle forecaster of the University of Málaga

(UMASEP). In all cases GLE Alert Plus precedes the GOES alert by ≈8–52 min. The comparison with UMASEP demonstrated a remarkably good agreement. Real-time GLE alerts by *GLE Alert Plus* may be retrieved by **http://cosray.phys.uoa.gr/gle_alert_plus.html**, **http://www.nmdb.eu**, **nd** **http://swe.ssa.esa.int/web/guest/space-radiation**. An automated GLE alert email notification system is also available to interested users.

A study on the main periodicities in interplanetary magnetic field Bz component and geomagnetic AE index during HILDCAA events using wavelet analysis

A.M. **Souza**, E. Echer, M.J.A. Bolzan, R. Hajra

Journal of Atmospheric and Solar-Terrestrial Physics Volume 149, November **2016**, Pages 81–86

http://www.sciencedirect.com/science/article/pii/S136468261630253X?dgcid=raven_sd_via_email

The interplanetary and geomagnetic characteristics of **High-Intensity Long-Duration Continuous AE Activity** (**HILDCAA**) events are studied using wavelet analysis technique. The Morlet wavelet transform was applied to the 1 min interplanetary magnetic field (IMF) Bz component and the geomagnetic AE index during HILDCAA events. We have analyzed the AE data for the events occurring between 1975 and 2011, and the IMF Bz data (both in GSE and GSM) for the events between 1995 and 2011. We analyzed the scalograms and the global wavelet spectrum of the parameters. For 50% of all HILDCAA events, the main periodicities of the AE index are generally between 4 and 12 h. For the Bz component, the main periodicities were found to be less than 8 h for ~56% of times in GSM system and for ~54% of times in GSE system. It is conjectured that the periodicities might be associated with the Alfvén waves which have typical periods between 1 and 10 h. The results are discussed in the light of self organized criticality theory where the physical events have the capacity of releasing a considerable amount of energy in a short interval of time.

For **HILDCAA** see R. Hajra, E. Echer, B.T. Tsurutani, W.D. Gonzalez
Solar cycle dependence of High-Intensity Long-Duration Continuous AE Activity (HILDCAA) events, relativistic electron predictors?
J. Geophys. Res., 118 (2013), pp. 5626–5638

Achievements and Lessons Learned from Successful Small Satellite Missions for Space Weather-Oriented Research

Harlan E. **Spence**, Amir Caspi, Hasan Bahcivan, Jesus Nieves-Chinchilla, Geoff Crowley, James Cutler, Chad Fish, David Jackson, Therese Moretto Jørgensen, David Klumpar, Xinlin Li, James P. Mason, Nick Paschalidis, John Sample, Sonya Smith, Charles M. Swenson, Thomas N. Woods

Space Weather **Volume20, Issue7** e2021SW003031 **2022**

https://arxiv.org/ftp/arxiv/papers/2206/2206.02968.pdf

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021SW003031

When the first CubeSats were launched nearly two decades ago, few people believed that the miniature satellites would likely prove to be a useful scientific tool. Skeptics abounded. However, the last decade has seen the highly successful implementation of space missions that make creative and innovative use of fast-advancing CubeSat and small satellite technology to carry out important science experiments and missions. Several projects now have used CubeSats to obtain first-of-their-kind observations and findings that have formed the basis for high-profile engineering and science publications, thereby establishing without doubt the scientific value and broad utility of CubeSats. In this paper, we describe recent achievements and lessons learned from a representative selection of successful CubeSat missions with a space weather focus. We conclude that these missions were successful in part because their limited resources promoted not only mission focus but also appropriate risk-taking for comparatively high science return. Quantitative analysis of refereed publications from these CubeSat missions and several larger missions reveals that mission outcome metrics compare favorably when publication number is normalized by mission cost or if expressed as a weighted net scientific impact of all mission publications. **May 22, 2012, 02 Feb 2015, 21-23 Jul 2016**

Impact of the 24 September 2011 Solar Radio Burst on the performance of GNSS Receivers†

V. **Sreeja**1,*, M. Aquino, 1, Kees de Jong

Space Weather, **2013**

Intense solar radio bursts occurring at the L-band frequencies can significantly impact the performance of Global Navigation Satellite System (GNSS) receivers in the sunlit hemisphere of the Earth. An intense solar radio burst occurred on **24 September 2011**, with a maximum power of 110,000 solar flux units (10-22 W/m2/Hz) at 1.415 GHz. This manuscript aims to contribute insight on the impact of this solar radio burst on the performance of the GNSS receivers in the European and Latin American sectors. Maximum reductions of 11.0, 22.0 and 10.0 dB-Hz in the carrier-to-noise density ratio (C/N0) of the GPS L1C/A, L2P and L2C signals respectively, were observed. The C/N0 reduction is modulated by the local solar incidence angle for the GPS L1C/A and L2P signals, whereas such modulation was not observed for the GPS L2C signal. The solar radio burst also had an adverse effect on the recorded GNSS pseudorange and carrier phase data, thereby causing positioning errors, which are also presented herein.

Editorial: Space Weather Prediction: Challenges and Prospects. **Review**
Srivastava N, Mierla M and Zhang J
(**2021**) Front. Astron. Space Sci. 8:818878. doi: 10.3389/fspas.2021.818878
https://www.frontiersin.org/articles/10.3389/fspas.2021.818878/full
https://doi.org/10.3389/fspas.2021.818878

Ionospheric Weather During Five Extreme Geomagnetic Superstorms Since IGY Deduced With the Instantaneous Global Maps GIM-foF2
Iwona **Stanislawska**, Tamara L. Gulyaeva, Oksana Grynyshyna-Poliuga, Ljubov V. Pustovalova
Space Weather 16?, 12, 2068-2078 **2018**
sci-hub.tw/10.1029/2018SW001945
An assessment of the ionosphere perturbations can be made through the construction of the global instantaneous maps of the foF2 critical frequency (GIM-foF2) and the ionospheric weather index maps GIM-Wf. These maps can offer a potentially useful tool to provide users with a proper selection of the best radio wave propagation conditions over a certain area and also be used to help mitigate the effects of the disturbances on HF (High Frequency) communication and Global Navigation Satellite System positioning. This paper presents results of reconstruction of the ionospheric weather during five of the most intense superstorms observed since International Geophysical Year, IGY (1957, 1958, 1959, 1989, and 2003) with the instantaneous global maps of the F2 layer critical frequency, GIM-foF2, and the ionospheric weather index maps, GIM-Wf. The intensity of the ionospheric superstorm is characterized by the planetary Wfp index derived from GIM-Wf maps. Superposed epoch analysis of the extreme superstorms is made during 24 hr before the Wfp peak (time zero t0 = 0 hr) and 48 hr afterwards. Model relationship is established between mean Wfp profile and geomagnetic superstorm profiles demonstrating saturation of the ionospheric storm activity toward the peak of geomagnetic storm. Time lag of Wfpmax is found equal to 9 hr after AEmax, 6 hr after apmax and aamax, and 2 hr after Dstmin, which allows model forecast of ionospheric superstorm when geomagnetic superstorm is captured with one or more of geomagnetic indices.

Using PC indices to predict violent GIC events threatening power grids
Peter **Stauning***
J. Space Weather Space Clim. **2020**, 10, 3
https://www.swsc-journal.org/articles/swsc/pdf/2020/01/swsc190040.pdf
The aim of the present contribution is to investigate the timing relations between enhancements in the Polar Cap (PC) indices and power grid disturbances related to geomagnetically induced currents (GIC). The polar cap indices, PCN (North) and PCS (South), are based on measurements of geomagnetic variations in the central polar caps. These variations are strongly related to the transpolar convection of plasma and magnetic fields driven by the solar wind. During cases of enhanced merging processes at the front of the magnetosphere and subsequent tailward convection of plasma and embedded magnetic fields, the magnetospheric tail configuration may accumulate excess energy, which upon release may cause violent substorm activity. Earlier reports have disclosed remarkably lengthy intervals, ranging up to several hours, of elevated PC index values preceding GIC-related power grid disruptions. The present investigation has shown that the delays of typically 3–4 h between increases in the PC indices and GIC-related power grid disturbances are related to displacements of the substorm processes responsible for strong GIC events to subauroral latitudes where vulnerable power grids reside. The results have shown that PC index values remaining above an “alert level” of 10 mV/m through more than 1 h indicate a high risk for violent GIC events that may threaten power grids and other vulnerable technical systems. These results support the application of real-time PC indices in space weather monitoring and forecast services. **Polar Cap (PC) index**

From Predicting Solar Activity to Forecasting Space Weather: Practical Examples of Research-to-Operations and Operations-to-Research
R. A. **Steenburgh**, D. A. Biesecker, G. H. Millward
Solar Physics, February **2014**, Volume 289, Issue 2, pp 675-690; **File**
The successful transition of research to operations (R2O) and operations to research (O2R) requires, above all, interaction between the two communities. We explore the role that close interaction and ongoing communication played in the successful fielding of three separate developments: an observation platform, a numerical model, and a visualization and specification tool. Additionally, we will examine how these three pieces came together to revolutionize interplanetary coronal mass ejection (ICME) arrival forecasts. A discussion of the importance of education and training in ensuring a positive outcome from R2O activity follows. We describe efforts by the meteorological community to make research results more accessible to forecasters and the applicability of these

efforts to the transfer of space-weather research. We end with a forecaster "wish list" for R2O transitions. Ongoing, two-way communication between the research and operations communities is the thread connecting it all.
2. The Practice of Space Weather Forecasting
3.1 The STEREO Mission
3.2 The WSA–Enlil Model
3.3 The CME Analysis Tool (CAT)

Automatic recognition of complex magnetic regions on the Sun in GONG magnetogram images and prediction of flares: Techniques for the flare warning program Flarecast

Steward, Graham A.; Lobzin, Vasili V.; Wilkinson, Phil J.; Cairns, Iver H.; Robinson, Peter A.
Space Weather, Vol. 9, No. 11, S11004, **2011**
http://dx.doi.org/10.1029/2011SW000703
In the present paper, Global Oscillation Network Group (GONG) solar magnetograms are used to automatically identify active regions by thresholding the line-of-sight component of the solar magnetic field. The flare potential of the regions is predicted by locating strong-gradient polarity inversion lines (SPILs) and estimating their parameters. The parameters of interest are the length of the SPIL, a proxy for its curvature; the maximum west-east and south-north gradients of the magnetic field in its vicinity; and a sum of the magnetic field gradients, the summation being performed along the SPIL. Analysis for thresholding of one, two, and three parameters and the corresponding probabilities for correct prediction of flares are presented and compared. The probability for correct prediction of X-ray flares of class C or greater in a 24 h window exceeds 88%, while the probability of false alarms is less than 10% if the decision rule involves thresholding of three specific parameters. These parameters are the steepest south-north gradient of the magnetic field, the maximum curvature of the SPILs, and the length of the longest SPIL, all being calculated for the entire region rather than for a particular SPIL. The steepest south-north gradient of the magnetic field is also used to estimate the probabilities for a flare to belong to classes C, M, or X. These techniques are now implemented in the flare warning program **Flarecast**. The first automatically predicted M- and X-class flares are presented, and Flarecast is found to predict well the observed X-ray flares.

A Space Weather Mission Concept: Observatories of the Solar Corona and Active Regions (OSCAR)

Antoine **Strugarek**, Nils Janitzek, Arrow Lee, Philipp Löschl, Bernhard Seifert, Sanni Hoilijoki, Emil Kraaikamp, Alankrita Isha Mrigakshi, Thomas Philippe, Sheila Spina, Malte Bröse, Sonny Massahi, Liam O'Halloran, Victor Pereira Blanco, Christoffer Stausland, Philippe Escoubet, Günter Kargl
Space Weather and Space Climate, 5, A4 **2015;**
http://arxiv.org/pdf/1409.0458v1.pdf
http://www.swsc-journal.org/articles/swsc/pdf/2015/01/swsc140008.pdf **, File**
Coronal Mass Ejections (CMEs) and Corotating Interaction Regions (CIRs) are major sources of magnetic storms on Earth and are therefore considered to be the most dangerous space weather events. The Observatories of Solar Corona and Active Regions (OSCAR) mission is designed to identify the 3D structure of coronal loops and to study the trigger mechanisms of CMEs in solar Active Regions (ARs) as well as their evolution and propagation processes in the inner heliosphere. It also aims to provide monitoring and forecasting of geo-effective CMEs and CIRs. OSCAR would contribute to significant advancements in the field of solar physics, improvements of the current CME prediction models, and provide data for reliable space weather forecasting. These objectives are achieved by utilising two spacecraft with identical instrumentation, located at a heliocentric orbital distance of 1~AU from the Sun. **The spacecraft will be separated by an angle of 68∘ to provide optimum stereoscopic view of the solar corona. We study the feasibility of such a mission and propose a preliminary design for OSCAR.**
Erratum J. Space Weather Space Clim., 7, A1 (**2017**)

Predictive Capabilities of Avalanche Models for Solar Flares

A. **Strugarek**, P. Charbonneau
Solar Physics, July **2014**
We assess the predictive capabilities of various classes of avalanche models for solar flares. We demonstrate that avalanche models cannot generally be used to predict specific events because of their high sensitivity to the embedded stochastic process. We show that deterministically driven models can nevertheless alleviate this caveat and be efficiently used for predictions of large events. Our results suggest a new approach for predictions of large (typically X-class) solar flares based on simple and computationally inexpensive avalanche models.

Predicting the energetic proton flux with a machine learning regression algorithm

Mirko **Stumpo**, Monica Laurenza, Simone Benella, Maria Federica Marcucci
ApJ **975** 8 **2024**
https://arxiv.org/pdf/2406.12730

https://iopscience.iop.org/article/10.3847/1538-4357/ad7734/pdf
The need of real-time of monitoring and alerting systems for Space Weather hazards has grown significantly in the last two decades. One of the most important challenge for space mission operations and planning is the prediction of solar proton events (SPEs). In this context, artificial intelligence and machine learning techniques have opened a new frontier, providing a new paradigm for statistical forecasting algorithms. The great majority of these models aim to predict the occurrence of a SPE, i.e., they are based on the classification approach. In this work we present a simple and efficient machine learning regression algorithm which is able to forecast the energetic proton flux up to 1 hour ahead by exploiting features derived from the electron flux only. This approach could be helpful to improve monitoring systems of the radiation risk in both deep space and near-Earth environments. The model is very relevant for mission operations and planning, especially when flare characteristics and source location are not available in real time, as at Mars distance. **October 25, 2000**
Table

Specification of > 2 MeV electron flux as a function of local time and geomagnetic activity at geosynchronous orbit

Yi-Jiun **Su***, Jack M. Quinn, W. Robert
Johnston, James P. McCollough andMichael J. Starks
Space Weather, Volume 12, Issue 7, pages 470–486, July **2014**
An algorithm has been developed for specifying > 2 MeV electron flux everywhere along geosynchronous orbit for use in operational products. The statistics of integrated electron fluxes from four GOESs for more than a solar cycle clearly indicate that the local time variation can be represented by a Gaussian distribution as a function of geomagnetic Kp index, which empirically determines the center and the half width of the Gaussian distribution. Using the most current estimated 3 h Kp value as an input, the prediction scheme requires the most recent electron flux measurements from available GOES(s) to determine the maximum and minimum for a Gaussian fit and to provide estimated electron fluxes at geosynchronous orbit with the time resolution of the instrument. In balancing between sufficient data for statistics and the change of geomagnetic configuration, the optimal length of data accumulation time for nowcasting is 6 h when one or two satellites are available. The prediction efficiency (PE) is independent of local time and solar cycle. We found that the PE values are greater than 0.5 when Kp < 5 and independent of Kp at low and moderate values; however, PE decreases dramatically with increasing Kp when Kp ≥ 5. Although the PE varies from year to year and with the choice of the test satellite, our finding resulted in a PE > 0.6 in 67.6% of the cases and PE > 0.8 more than 23.5% of the time based on our analysis from four GOESs between 1998 and 2009. Moreover, skill scores from our newly developed algorithm are ~90% of the time better than those resulting from a simpler algorithm based on a table provided by O'Brien (2009), indicating a dramatic improvement in predictive capability.

Solar Wind Speed Prediction With Two-Dimensional Attention Mechanism

Yanru **Sun**, Zongxia Xie, Yanhong Chen, Xin Huang, Qinghua Hu
Space Weather **Volume19, Issue7** e2020SW002707, **2021**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020SW002707
https://doi.org/10.1029/2020SW002707
As more and more high-technical systems are exposed to the space environment, extreme space weather becomes a great threat to human society. In the solar system, space weather is influenced by the solar wind, such that reliable prediction of solar wind conditions in the near-Earth environment effectively reduces the impact of space weather on human society. Solar wind speed prediction is improved by making full use of OMNI data measured at Lagrangian Point 1 (L1) by the National Aeronautics and Space Administration (NASA) and image data observed by the Solar Dynamics Observatory (SDO) satellite in this work. Specifically, we propose a model based on the **"two-dimensional attention mechanism" (TDAM)** to predict solar wind speed. In this study, we first analyze and preprocess data from 2011 to 2017. Second, considering the characteristics of time series data, we adopt the gated recurrent units (GRU) model which can deal with long-term dependence as the prediction part of our model. Third, we design a TDAM, which enables our prediction network to focus on important parts. Three performance indices are used: root-mean-square error (RMSE), mean absolute error (MAE), and correlation coefficient (CC). By comparing TDAM with other models, we find that the TDAM model achieves the best prediction results, with RMSE of 62.8 km/s, MAE of 47.8 km/s, and CC of 0.789 24 h in advance. The experimental results show that the proposed TDAM model can improve the prediction accuracy of solar wind speed.

A New Method of Physics-Based Data Assimilation for the Quiet and Disturbed Thermosphere

Sutton, Eric K.
Space Weather, Volume 16, Issue 6, pp. 736-753 **2018**

The ability to accurately track and predict satellite locations is of paramount importance to space-faring nations. In the low Earth orbit satellite environment, atmospheric drag is by far the dominant error associated with orbit propagation. Nowcasts of thermospheric density are routinely accomplished through calibration of semiempirical models using recent data, yet forward predictions degrade quickly as lead time increases. Physics-based approaches offer a great forecasting potential but one that has yet to be realized due to a lack of robust data assimilation schemes. In an effort to account for the driver/response characteristics of the thermosphere-ionosphere system, a new data assimilative technique is developed. Abandoning the ensemble Kalman filter framework in favor of a variational technique, iterative model reinitialization is applied self-consistently to estimate a time history of effective solar and geophysical drivers. The current implementation of this technique, referred to as Iterative Reinitialization, Driver Estimation and Assimilation, works by ingesting neutral mass density measurements from low-Earth orbiting accelerometers. A long-term simulation is carried out during 2003, a period consisting of a wide range of solar and geomagnetic activity levels. The new technique is shown to greatly reduce RMS errors of the physics-based model relative to ingested observations from the Challenging Mini-Satellite Payload (CHAMP) satellite as well as to an independent validation data set from the Gravity Recovery And Climate Experiment (GRACE) satellite. This work is the first such demonstration of an accurate and robust physics-based method capable of specifying neutral density during both quiet and disturbed times and offers a promising outlook for improving density forecasting capabilities.
See Space Weather Quarterly Vol. 15, Issue 2, **2018**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/swq.18

Solar Energetic Particle Forecasting Algorithms and Associated False Alarms

Bill **Swalwell**, Silvia Dalla, Robert Walsh

Solar Phys.   292:173   **2017 File**

https://arxiv.org/pdf/1710.08156.pdf

Solar energetic particle (SEP) events are known to occur following solar flares and coronal mass ejections (CMEs). However some high-energy solar events do not result in SEPs being detected at Earth, and it is these types of event which may be termed "false alarms".
We define two simple SEP forecasting algorithms based upon the occurrence of a magnetically well-connected CME with a speed in excess of 1500 km/s ("a fast CME") or a well-connected X-class flare and analyse them with respect to historical data sets. We compare the parameters of those solar events which produced an enhancement of >40 MeV protons at Earth ("an SEP event") and the false alarms. We find that an SEP forecasting algorithm based solely upon the occurrence of a well-connected fast CME produces fewer false alarms (28.8%) than one based solely upon a well-connected X-class flare (50.6%). Both algorithms fail to forecast a relatively high percentage of SEP events (53.2% and 50.6% respectively). Our analysis of the historical data sets shows that false alarm X-class flares were either not associated with any CME, or were associated with a CME slower than 500 km/s; false alarm fast CMEs tended to be associated with flares of class less than M3.
A better approach to forecasting would be an algorithm which takes as its base the occurrence of both CMEs and flares. We define a new forecasting algorithm which uses a combination of CME and flare parameters and show that the false alarm ratio is similar to that for the algorithm based upon fast CMEs (29.6%), but the percentage of SEP events not forecast is reduced to 32.4%. Lists of the solar events which gave rise to >40 MeV protons and the false alarms have been derived and are made available to aid further study.
Table 5. List of fast CMEs between 1 January 1996 and 31 March 2013 which were false alarms.
Table 6. List of X-class flares between 1 January 1996 and 31 March 2013 which were false alarms. C
Table 7. List of X-class flares between 1 April 1980 and 31 December 1995 which were false alarms

Effects of Forbush Decreases on the Global Electric Circuit

J. **Tacza**, G. Li, J.-P. Raulin

Space Weather 2024 Volume22, Issue4 April **2024** e2023SW003852

https://doi.org/10.1029/2023SW003852

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2023SW003852

The suppression of high-energy cosmic rays, known as Forbush decreases (FDs), represents a promising factor in influencing the global electric circuit (GEC) system. Researchers have delved into these effects by examining variations, often disruptive, of the potential gradient (PG) in ground-based measurements taken in fair weather regions. In this paper, we aim to investigate deviations observed in the diurnal curve of the PG, as compared to the mean values derived from fair weather conditions, during both mild and strong Forbush decreases. Unlike the traditional classification of FDs, which are based on ground level neutron monitor data, we classify FDs using measurements of the Alpha Magnetic Spectrometer (AMS-02) on the International Space Station. To conduct our analysis, we employ the superposed epoch method, focusing on PGs collected between January 2010 and December 2019 at a specific station situated at a low latitude and high altitude: the Complejo Astronómico El Leoncito (CASLEO) in Argentina (31.78°S, 2,550 m above sea level). Our findings reveal that for events associated with FDs having flux amplitude (A) decrease ≤10%, no significant change in the PG is observed. However, for FDs with A > 10%, a clear increase in the PG is seen. For these A > 10% events, we also find a good correlation between the variation of Dst and Kp indices and the variation of PG.

Investigating effects of solar proton events and Forbush decreases on ground-level potential gradient recorded at middle and low latitudes and different altitudes

J. **Tacza**, A. Odzimek, E. Tueros Cuadros, J.-P. Raulin, M. Kubicki, G. Fernandez, A. Marun

Space Weather **Volume20, Issue3** e2021SW002944 **2022**

https://doi.org/10.1029/2021SW002944

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021SW002944

High-energetic charged particles, such as solar protons, and phenomena such as Forbush decreases are eligible candidates to affect the global electric circuit. These effects have been studied by analyzing disturbances of the potential gradient in ground-based measurements in fair weather regions. In this paper, we investigate deviations in the potential gradient diurnal curve, during solar proton events and Forbush decreases, from the mean values obtained in fair weather conditions. In each situation we select only events which are not accompanied or followed by the other. Using the superposed epoch analysis, in order to enhance the visualization of small effects, we study the potential gradient data recorded between January 2010 and December 2019 at two stations located at low and middle-latitudes, and at two different altitudes: the Complejo Astronómico El Leoncito (CASLEO), Argentina: 31.78°S, 2550 m a.s.l., and the Geophysical Observatory in Świder (SWIDER), Poland: 52.12°N, 100 m a.s.l., respectively. For intense solar proton events (>100 MeV) we found a statistically significant increase of the potential gradient after solar proton events recorded at CASLEO and no such deviation in the potential gradient recorded at SWIDER. For Forbush decrease events (greater than 4%), no significant deviation of the potential gradient after the start of the event was found in both stations, however for very intense Forbush decreases (>7%) we found an increase of the potential gradient recorded at CASLEO.
Table A1. List of the Solar Proton Events chosen for our analysis (2011-2017
Table B1. List of the Forbush decreases events chosen for our Analysis)

Monitoring Coronal Mass Ejections and Space Weather at NASA Goddard Space Flight Center

A. **Taktakishvili**, A. Pulkkinen, Y.Zheng, L. Mays, P. MacNeice, M. Kuznetsova

ИКИ-**2014**, Сессия: Солнечный ветер, гелиосфера и солнечно-земные связи

http://plasma2014.cosmos.ru/presentations

From space weather toward space climate time scales: Substorm analysis from 1993 to 2008

Tanskanen, E. I.; Pulkkinen, T. I.; Viljanen, A.; Mursula, K.; Partamies, N.; Slavin, J. A.

J. Geophys. Res., Vol. 116, No. null, A00I34, **2011**

Magnetic activity in the Northern Hemisphere auroral region was examined during solar cycles 22 and 23 (1993–2008). Substorms were identified from ground-based magnetic field measurements by an automated search engine. On average, 550 substorms were observed per year, which gives in total about 9000 substorms. The interannual, seasonal and solar cycle-to-cycle variations of the substorm number (Rss), substorm duration (Tss), and peak amplitude (Ass) were examined. The declining phases of both solar cycles 22 and 23 were more active than the other solar cycle phases due to the enhanced solar wind speed. The spring substorms during the declining solar cycle phase (|Ass,decl| = 500 nT) were 25% larger than the spring substorms during the ascending solar cycle years (|Ass,acs| = 400 nT). The following seasonal variation was found: the most intense substorms occurred during spring and fall, the largest substorm frequency in the Northern Hemisphere winter, and the longest-duration substorms in summer. Furthermore, we found a winter-summer asymmetry in the substorm number and duration, which is speculated to be due to the variations in the ionospheric conductivity. The solar cycle-to-cycle variation was found in the yearly substorm number and peak amplitude. The decline from the peak substorm activity in 1994 and 2003 to the following minima took 3 years during solar cycle 22, while it took 6 years during solar cycle 23.

Changing Relationships Between Sunspot Number, Total Sunspot Area and F10.7 in Cycles 23 and 24

Ken **Tapping**, Carly Morgan

Solar Phys. (**2017**) 292: 73. doi:10.1007/s11207-017-1111-6

This article is an update of a study (Tapping and Valdès in Solar Phys.272, 337, 2011) made in the early part of Cycle 24 using an intercomparison of various solar activity indices (including sunspot number and the 10.7 cm solar radio flux), in which it was concluded that a change in the relationship between photospheric and chromospheric/coronal activity took place just after the maximum of Cycle 23 and continued into Cycle 24. Precursors (short-term variations) were detected in Cycles 21 and 22. Since then the sunspot number index data have been substantially revised. This study is intended to be an update of the earlier study and to assess the impact of the revision of the sunspot number data upon those conclusions. This study compares original and revised sunspot number, total sunspot area, and 10.7 cm solar radio flux. The conclusion is that the transient changes in Cycles 21 and 22, and the more substantial change in Cycle 23, remain evident. Cycle 24 shows indications that the deviation was probably another short-term one.

The 10.7 cm solar radio flux (F10.7)
K. F. **Tapping**
Space Weather, Volume 11, Issue 7, pages 394–406, July **2013**
The 10.7 cm solar radio flux, or F10.7 is, along with sunspot number, one of the most widely used indices of solar activity. This paper describes the equipment and procedures used to make the measurements and to calibrate them, and discusses some of the “most-asked” questions about the data.

The Next Generation of Canadian Solar Flux Monitoring
Tapping, Kenneth F.; Morton, Donald C.
Journal of Physics: Conference Series, Volume 440, Issue 1, article id. 012039 (**2013**).
The 10.7 cm solar radio flux (F10.7), provided by the National Research Council of Canada since 1947, is widely used as an index of solar activity and as a proxy for other solar quantities that are harder to measure. Over recent years needs have arisen that are difficult to meet with solar flux measurements at a single wavelength. F10.7 comprises contributions from multiple emission mechanisms. To separate these, multi-wavelength measurements are needed. A new instrument is under construction that will measure fluxes precisely in six bands at 2.8, 3.6, 6.0, 10.7, 18 and 21 cm.

Editorial: Magnetic Connectivity of the Earth and Planetary Environments to the Sun in Space Weather Studies
Daniele **Telloni**1*, Zoltan Vörös2, Emiliya Yordanova3 and Raffaella D’Amicis4
Front. Astron. Space Sci. 9:853925. **2022**
https://doi.org/10.3389/fspas.2022.853925
https://www.frontiersin.org/articles/10.3389/fspas.2022.853925/full

Understanding Space Weather - an interdisciplinary filed of research
Manuela **Temmer**
The tenth webinar on the International Space Weather Initiative, 29 March **2023**,
Now available on the YouTube channel of the Office: https://youtu.be/Tnx7NDB4J78

Space weather: the solar perspective -- an update to Schwenn (2006) **Review**
Manuela **Temmer**
Living Reviews in Solar Physics **18**, 4 **2021**
https://arxiv.org/pdf/2104.04261.pdf
https://link.springer.com/content/pdf/10.1007/s41116-021-00030-3.pdf **File**
https://doi.org/10.1007/s41116-021-00030-3
The Sun, as an active star, is the driver of energetic phenomena that structure interplanetary space and affect planetary atmospheres. The effects of Space Weather on Earth and the solar system is of increasing importance as human spaceflight is preparing for lunar and Mars missions. This review is focusing on the solar perspective of the Space Weather relevant phenomena, coronal mass ejections (CMEs), flares, solar energetic particles (SEPs), and solar wind stream interaction regions (SIR). With the advent of the STEREO mission (launched in 2006), literally, new perspectives were provided that enabled for the first time to study coronal structures and the evolution of activity phenomena in three dimensions. New imaging capabilities, covering the entire Sun-Earth distance range, allowed to seamlessly connect CMEs and their interplanetary counterparts measured in-situ (so called ICMEs). This vastly increased our knowledge and understanding of the dynamics of interplanetary space due to solar activity and fostered the development of Space Weather forecasting models. Moreover, we are facing challenging times gathering new data from two extraordinary missions, NASA's Parker Solar Probe (launched in 2018) and ESA's Solar Orbiter (launched in 2020), that will in the near future provide more detailed insight into the solar wind evolution and image CMEs from view points never approached before. The current review builds upon the Living Reviews paper by Schwenn from 2006, updating on the Space Weather relevant CME-flare-SEP phenomena from the solar perspective, as observed from multiple viewpoints and their concomitant solar surface signatures**. 5-8 Dec 1981, 13-16 Aug 1982, 12 July 2007, December 12, 2008, December 22, 2009, 10 Jun 2010, June 12-13, 2010, 28 Oct 2003, November 18, 2003, 6-8 Aug 2007, March 7, 2011, August 9, 2011, March 7–11, 2012: May 17, 2012, June 30, 2012, 2-4 Dec 2012, June 14, 2012, February 25, 2014, August 24, 2014, January 1, 2016, September 6, 2017, 6-12 Sep 2017,**

Coronal hole evolution from multi-viewpoint data as input for a STEREO solar wind speed persistence model
M. **Temmer**, J. Hinterreiter, M.A. Reiss
Journal of Space Weather and Space Climate (SWSC) **2018**
https://arxiv.org/pdf/1801.10213.pdf

We present a concept study of a solar wind forecasting method for Earth, based on persistence modeling from STEREO in-situ measurements combined with multi-viewpoint EUV observational data. By comparing the fractional areas of coronal holes (CHs) extracted from EUV data of STEREO and SoHO/SDO, we perform an uncertainty assessment derived from changes in the CHs and apply those changes to the predicted solar wind speed profile at 1AU. We evaluate the method for the time period 2008-2012, and compare the results to a persistence model based on ACE in-situ measurements and to the STEREO persistence model without implementing the information on CH evolution. Compared to an ACE based persistence model, the performance of the STEREO persistence model which takes into account the evolution of CHs, is able to increase the number of correctly predicted high-speed streams by about 12%, and to decrease the number of missed streams by about 23%, and the number of false alarms by about 19%. However, the added information on CH evolution is not able to deliver more accurate speed values for the forecast than using the STEREO persistence model without CH information which performs better than an ACE based persistence model. Investigating the CH evolution between STEREO and Earth view for varying separation angles over ~25-140{\deg} East of Earth, we derive some relation between expanding CHs and increasing solar wind speed, but a less clear relation for decaying CHs and decreasing solar wind speed. This fact most likely prevents the method from making more precise forecasts. The obtained results support a future L5 mission and show the importance and valuable contribution using multi-viewpoint data.

Evaluating the Skill of Forecasts of the Near-Earth Solar Wind Using a Space Weather Monitor at L5

S. R. **Thomas** , A. Fazakerley , R. T. Wicks , L. Green
Space Weather Volume16, Issue7 July **2018** Pages 814-828
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2018SW001821

Forecasting space weather is an essential activity for increasing the resilience of modern technological infrastructure to hazards from the Sun. To provide an accurate forecast, space weather monitors positioned at L5 are proposed that carry in situ plasma detectors. Here we use data from the STEREO and ACE missions to investigate how well it is possible to predict the solar wind when there are two spacecraft located with the same longitudinal separation as from L5 to Earth. There are four intervals when this is the case: STEREO-to-STEREO both on the Earth's side and the far side of the Sun, STEREO-B to ACE and ACE to STEREO-A. We forecast the solar wind by mapping the observed solar wind at the first spacecraft to the second using a time delay calculated using the spacecraft's heliographic longitudinal separation and the difference in radial distance from the Sun, allowing for the solar wind speed. Using forecasting skill scores, we find that the predicted and observed solar wind data are, in general, in very good agreement with each of the four periods, including observed corotating interaction regions. However, there are some notable exceptions when corotating interaction regions have been missed by the forecast. The skill improves further for all time periods when removing coronal mass ejections, which cannot be predicted in this method. We suggest that an L5 monitor should be located at the same heliographic latitude as the Earth to optimize the forecasting ability of the monitor and to reduce the chance of missing important events.

Current STEREO Status on the Far Side of the Sun

Thompson, William T.; Gurman, Joseph; Ossing, Daniel; Luhmann, Janet; Curtis, David; Schroeder, Peter; Mewaldt, Richard; Davis, Andrew; Wortman, Kristin; Russell, Christopher; and 10 coauthors
Joint American Astronomical Society/American Geophysical Union Triennial Earth-Sun Summit, meeting #1, #402.05, 04/**2015**

The current positions of the two STEREO spacecraft on the opposite side of the Sun from Earth (superior solar conjunction) has forced some significant changes in the spacecraft and instrument operations. No communications are possible when the spacecraft is within 2 degrees of the Sun, requiring that the spacecraft be put into safe mode until communications can be restored. Unfortunately, communications were lost with the STEREO Behind spacecraft on October 1, 2014, during testing for superior solar conjunction operations. We will discuss what is known about the causes of loss of contact, the steps being taken to try to recover the Behind spacecraft, and what has been done to prevent a similar occurrence on STEREO Ahead.We will also discuss the effect of being on the far side of the Sun on the science operations of STEREO Ahead. Starting on August 20, 2014, the telemetry rate from the STEREO Ahead spacecraft has been tremendously reduced due to the need to keep the temperature of the feed horn on the high gain antenna below acceptable limits. However, the amount of telemetry that can be brought down has been highly reduced. Even so, significant science is still possible from STEREO's unique position on the solar far side. We will discuss the science and space weather products that are, or will be, available from each STEREO instrument, when those products will be available, and how they will be used. Some data, including the regular space weather beacon products, are brought down for an average of a few hours each day during the daily real-time passes, while the in situ and radio beacon data are being stored on the onboard recorder to provide a continuous 24-hour coverage for eventual downlink once the spacecraft is back to normal operations.

Analytical Representations for Characterizing the Global Aviation Radiation Environment Based on Model and Measurement Databases

W. Kent **Tobiska** Leonid Didkovsky Kevin Judge et al.
Space Weather Volume16, Issue10 October **2018** Pages 1523-1538
https://doi.org/10.1029/2018SW001843
http://sci-hub.tw/10.1029/2018SW001843

The Nowcast of Atmospheric Ionizing Radiation for Aviation Safety climatological model and the Automated Radiation Measurements for Aerospace Safety (ARMAS) statistical database are presented as polynomial fit equations. Using equations based on altitude, L shell, and geomagnetic conditions an effective dose rate for any location from a galactic cosmic ray (GCR) environment can be calculated. A subset of the ARMAS database is represented by a second polynomial fit equation for the GCR plus probable relativistic energetic particle (REP; Van Allen belt REP) effective dose rates within a narrow band of L shells with altitudinal and geomagnetic dependency. Solar energetic particle events are not considered in this study since our databases do not contain these events. This work supports a suggestion that there may be a REP contribution having an effect at aviation altitudes. The ARMAS database is rich in Western Hemisphere observations for L shells between 1.5 and 5; there have been many cases of enhanced radiation events possibly related to effects from radiation belt particles. Our work identifies that the combined effects of an enhanced radiation environment in this L shell range are typically 15% higher than the GCR background. We also identify applications for the equations representing the Nowcast of Atmospheric Ionizing Radiation for Aviation Safety and ARMAS databases. They include (i) effective dose rate climatology in comparison with measured weather variability and (ii) climatological and statistical weather nowcasting and forecasting. These databases may especially help predict the radiation environment for regional air traffic management, for airport overflight operations, and for air carrier route operations of individual aircraft.

Chapter 18 - Characterizing the Variation in Atmospheric Radiation at Aviation Altitudes

W. Kent **Tobiska***†Matthias M.Meier‡DanielMatthiae‡KyleCopeland§ **Review**
In: Extreme Events in Geospace Origins, Predictability, and Consequences **2018**, Pages 453-471
http://sci-hub.tw/10.1016/B978-0-12-812700-1.00018-2

For astronauts and travelers in aircraft, space weather can quickly increase dose rates resulting from naturally occurring ionizing radiation by more than a 1000-fold. Historically, monitoring of these events has been done primarily by a combination of ground-based and satellite instrumentation. At best, these data sources provide a local (ground-level monitors) or global (satellite) average picture of an event as it evolves. With considerable modeling effort, a better global picture of an event emerges after the event has passed. For aviation users this is inadequate. Real-time local estimates on flight routes are preferred to enable appropriate responses from pilots and air traffic management. Modeling and measurement programs are described, and a new aviation dose index is discussed to provide examples of systems that are in development or that have been recently adopted for addressing problems with the current monitoring, warning, and evaluation methods.

Advances in Atmospheric Radiation Measurements and Modeling Needed to Improve Air Safety

Tobiska, W.K., Atwell, W., Beck, P., Benton, E., Copeland, K., Dyer, ...
2015, Space Weather 13(4), 202
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2015SW001169

Air safety is tied to the phenomenon of ionizing radiation from space weather, primarily from galactic cosmic rays but also from solar energetic particles. A global framework for addressing radiation issues in this environment has been constructed, but more must be done at international and national levels. Health consequences from atmospheric radiation exposure are likely to exist. In addition, severe solar radiation events may cause economic consequences in the international aviation community due to exposure limits being reached by some crew members. Impacts from a radiation environment upon avionics from high-energy particles and low-energy, thermalized neutrons are now recognized as an area of active interest. A broad community recognizes that there are a number of mitigation paths that can be taken relative to the human tissue and avionics exposure risks. These include developing active monitoring and measurement programs as well as improving scientific modeling capabilities that can eventually be turned into operations. A number of roadblocks to risk mitigation still exist, such as effective pilot training programs as well as monitoring, measuring, and regulatory measures. An active international effort toward observing the weather of atmospheric radiation must occur to make progress in mitigating radiation exposure risks. Stakeholders in this process include standard-making bodies, scientific organizations, regulatory organizations, air traffic management systems, aircraft owners and operators, pilots and crew, and even the public.

A Preliminary Risk Assessment of Geomagnetically Induced Currents over the Italian Territory

R. **Tozzi**, P. De Michelis, I. Coco, F. Giannattasio

Space Weather **2019**

http://sci-hub.tw/10.1029/2018SW002065

Geomagnetically induced currents (GICs), occurring as a result of space weather events, represent a hazard for the secure and safe operation of electrical power grids and oil/gas pipelines. The most exposed countries are those at high latitudes where, in the past, the occurrence of intense GICs has seriously damaged part of their power networks. However, very powerful space weather events have resulted in intense GICs also at middle and low latitudes. The GIC index is a proxy of the geoelectric field, and it can be estimated straightforwardly from magnetic observatory data. In this work, the GIC index is computed to investigate the possible impact of space weather events on the Italian territory. We first calculate the GIC index using data from the magnetic observatories of Castello Tesino, Duronia, and Lampedusa, together covering the whole Italian latitudinal extension, and show its behavior during the 2015 St. Patrick's day storm. Then, we consider measurements from the two longest running Italian magnetic observatories, that is, Castello Tesino and L'Aquila, and estimate the GIC index over more than 20 years of observations. A preliminary characterization of the general risk to which the Italian power grid network is exposed is given. Results show that during periods of high magnetic activity, potentially detrimental GICs could flow through the power network, especially at the highest Italian latitudes that are characterized by a low conductivity lithosphere.

Space Weather in Focus: A Decade in Review

Tretkoff, Ernie

Space Weather, Vol. 8, No. 10, S10008, **2010**

In the past decade, many events, discoveries, and publications have brought attention to how the Sun affects technologies, increasing awareness of space weather's effects among scientists, policy makers, and the public. As the decade comes to a close, Space Weather staff writers wondered what comes into focus after a quick scan of the past 10 years. After many excellent suggestions from Space Weather's editorial advisory board and our editor were reviewed, five snapshots were selected as representative of the most significant developments in space weather from 2001 to 2010. The items below are in no particular order.

Space Weather and Satellite Engineering: An Interview With Michael Bodeau,

Tretkoff, E.

(**2010**), Space Weather, 8, S03003, doi:10.1029/2010SW000584.

http://www.agu.org/pubs/crossref/2010/2010SW000584.shtml

Michael Bodeau is a technical fellow at Northrop Grumman. Over his career, which has included positions at TRW, Hughes, and Boeing, he has designed telecommunications and scientific satellites for government and commercial operators and has studied the effects of space weather on satellites. In this interview, Bodeau describes how satellite engineers create “building codes” to help them design satellites that can withstand space weather events.

Carrington-L5: The UK/US Operational Space Weather Monitoring Mission,

Trichas, M., Gibbs, M., Harrison, R., Green, L., Eastwood, J., Bentley, B., et al.

(**2015**), Hipparchos, vol. 2, Issue 12, pp. 25 - 31, 2, 12, 25–31

http://www.helas.gr/hipparchos/hipparchos_v2_12.pdf

Airbus Defence and Space (UK) has carried out a study to investigate the possibilities for an operational space weather mission, in collaboration with the Met Office, RAL, MSSL and Imperial College London. The study looked at the user requirements for an operational mission, a model instrument payload, and a mission/spacecraft concept. A particular focus is cost effectiveness and timelineness of the data, suitable for 24/7 operational forecasting needs. We have focussed on a mission at L5 assuming that a mission to L1 will already occur, on the basis that L5 (Earth trailing) offers the greatest benefit for the earliest possible warning on hazardous SWE events and the most accurate SWE predictions. The baseline payload has been selected to cover all UK Met Office/NOAA's users priorities for L5 using instruments with extensive UK/US heritage, consisting of: heliospheric imager, coronograph, magnetograph, magnetometer, solar wind analyser and radiation monitor. The platform and subsystems are based on extensive re-use from past Airbus Defence and Space spacecraft to minimize the development cost and a Falcon-9 launcher has been selected on the same basis. A schedule analysis shows that the earliest launch could be achieved by 2020, assuming Phase A kick-off in 2015-2016. The study team have selected the name "Carrington" for the mission, reflecting the UK's proud history in this domain.

November 2004 space weather events: Real time observations and forecasts

L. **Trichtchenko**, A.N. Zhukov, R.A.M. Van der Linden, S. M. Stankov, N. Jakowski, I. Stanislawska,

G. Juchnikowski, P. Wilkinson, G. Patterson, A. W. P. Thomson
Space Weather 5, S06001 (**2007**). **File**
Space weather events with their solar origin and their distribution through the heliosphere affect the whole magnetosphere-ionosphere-Earth system. Their real-time monitoring and forecasting are important for science and technology. Here we discuss one of the largest space weather events of Solar Cycle 23, in November 2004, which was also one of the most difficult periods to forecast. Nine halo coronal mass ejections (CMEs), interacting on their way through the interplanetary medium and forming two geoeffective interplanetary structures, exemplify the complexity of the event. Real-time and quasi-real-time observations of the ground geomagnetic field show rapid and extensive expansion of the auroral oval to 55_ in geomagnetic latitude accompanied by great variability of the ionosphere. Geomagnetically induced currents (GICs) seen in ground networks, such as power grids and pipelines, were significant during the event, although no problems were reported. Forecasts of the CME propagation, global and local ground geomagnetic activity, and ionospheric parameters, issued by several regional warning centers, revealed certain deficiencies in predictions of the interplanetary characteristics of the CME, size of the geomagnetic disturbances, and complexity of the ionospheric variations produced by this event. This paper is a collective report based on the materials presented at the splinter session on November 2004 events during the first European Space Weather Week.

Progress in space weather modeling in an operational environment **Review**
Ioanna **Tsagouri**1*, Anna Belehaki1, Nicolas Bergeot2,3, Consuelo Cid4, Véronique Delouille2,3, Tatiana Egorova5, Norbert Jakowski6, Ivan Kutiev7, Andrei Mikhailov8, Marlon Núñez9, Marco Pietrella10, Alexander Potapov11, Rami Qahwaji12, Yurdanur Tulunay13, Peter Velinov7 and Ari Viljanen
J. Space Weather Space Clim. 3 (**2013**) A17; **File**
This paper aims at providing an overview of latest advances in space weather modeling in an operational environment in Europe, including both the introduction of new models and improvements to existing codes and algorithms that address the broad range of space weather's prediction requirements from the Sun to the Earth.
3.1. Solar weather predictions
3.1.2. SPoCA-suite for Near-Real-Time detection and tracking of Active Regions and **Coronal Holes** on SDO-AIA data
3.1.3. The UMASEP for forecasting **SEP** events
3.2. Geomagnetic predictions

Advancing the understanding of the Sun-Earth interaction - the Climate and Weather of the Sun-Earth System (CAWSES) II program
Toshitada **Tsuda**, Marianna Shepherd and Nat Gopalswamy
Progress in Earth and Planetary Science **2015**, 2, 28
http://cdaw.gsfc.nasa.gov/publications/gopal/gopal2015PEPS_intro.pdf
The Scientific Committee on Solar-Terrestrial Physics (SCOSTEP) of the International Council for Science (ICSU) implemented an international collaborative program called Climate and Weather of the Sun-Earth System (CAWSES), which was active from 2004 to 2008; this was followed by the CAWSES II program during the period of 2009-2013. The CAWSES program was aimed at improving the understanding of the coupled solar-terrestrial system, with special emphasis placed on the short-term (weather) and long-term (climate) variability of solar activities and their effects on and responses of Geospace and Earth's environment. Following the successful implementation of CAWSES, the CAWSES II program pursued four fundamental questions addressing the way in which the coupled Sun-Earth system operates over time scales ranging from minutes to millennia, namely, (1) What are the solar influences on the Earth's climate? (2) How will Geospace respond to an altered climate? (3) How does short-term solar variability affect the Geospace environment? and (4) What is the Geospace response to variable inputs from the lower atmosphere? In addition to these four major tasks, the SCOSTEP and CAWSES promoted E-science and informatics activities including the creation of scientific databases and their effective utilization in solar-terrestrial physics research. Capacity building activities were also enhanced during CAWSES II, and this represented an important contribution of SCOSTEP to the world's solar-terrestrial physics community. This introductory paper provides an overview of CAWSES II activities and serves as a preface to the dedicated review papers summarizing the achievements of the program's four task groups (TGs) and the E-science component.

The physics of space weather/solar-terrestrial physics (STP): what we know now and what the current and future challenges are. **Review**
Tsurutani BT, Lakhina GS, Hajra R
(**2020**) Nonlinear Proc Geophys Volume 27, issue 1 NPG, 27, 75–119,
https://doi.org/10.5194/npg-27-75-2020

https://npg.copernicus.org/articles/27/75/2020/
https://sci-hub.ru/10.5194/npg-27-75-2020

Major geomagnetic storms are caused by unusually intense solar wind southward magnetic fields that impinge upon the Earth's magnetosphere (Dungey, 1961). How can we predict the occurrence of future interplanetary events? Do we currently know enough of the underlying physics and do we have sufficient observations of solar wind phenomena that will impinge upon the Earth's magnetosphere? We view this as the most important challenge in space weather. We discuss the case for magnetic clouds (MCs), interplanetary sheaths upstream of interplanetary coronal mass ejections (ICMEs), corotating interaction regions (CIRs) and solar wind high-speed streams (HSSs). The sheath- and CIR-related magnetic storms will be difficult to predict and will require better knowledge of the slow solar wind and modeling to solve. For interplanetary space weather, there are challenges for understanding the fluences and spectra of solar energetic particles (SEPs). This will require better knowledge of interplanetary shock properties as they propagate and evolve going from the Sun to 1 AU (and beyond), the upstream slow solar wind and energetic “seed” particles. Dayside aurora, triggering of nightside substorms, and formation of new radiation belts can all be caused by shock and interplanetary ram pressure impingements onto the Earth's magnetosphere. The acceleration and loss of relativistic magnetospheric “killer” electrons and prompt penetrating electric fields in terms of causing positive and negative ionospheric storms are reasonably well understood, but refinements are still needed. The forecasting of extreme events (extreme shocks, extreme solar energetic particle events, and extreme geomagnetic storms (Carrington events or greater)) are also discussed. Energetic particle precipitation into the atmosphere and ozone destruction are briefly discussed. For many of the studies, the Parker Solar Probe, Solar Orbiter, Magnetospheric Multiscale Mission (MMS), Arase, and SWARM data will be useful.

The Interplanetary and Magnetospheric causes of Geomagnetically Induced Currents (GICs) > 10 A in the Mäntsälä Finland Pipeline: 1999 through 2019

Bruce T. **Tsurutani** and Rajkumar Hajra
J. Space Weather Space Clim. **2021**, 11, 23
https://doi.org/10.1051/swsc/2021001
https://www.swsc-journal.org/articles/swsc/pdf/2021/01/swsc200089.pdf

The interplanetary and magnetospheric phenomena time-coincident with intense geomagnetically induced current (GIC) > 10 A and > 30 A events during 21 years (1999 through 2019) at the Mäntsälä, Finland (57.9° magnetic latitude) gas pipeline have been studied. Although forward shocks and substorms are predominant causes of intense GICs, some newly discovered geoeffective interplanetary features are: solar wind plasma parcel (PP) impingements, possible interplanetary magnetic field (IMF) northward (Bn) and southward (Bs) turnings, and reverse shocks. The PPs are possibly the loop and filament portions of coronal mass ejections (CMEs).
From a study of > 30 A GIC events, it is found that supersubstorm (SSS: SML < −2500 nT) and intense substorm (−2500 nT < SML < −2000 nT) auroral electrojet intensifications are the most frequent (76%) cause of all of these GIC events. These events occur most often (76%) in superstorm (SYM-H ≤ −250 nT) main phases, but they can occur in other storm phases and lesser intensity storms as well. After substorms, PPs were the most frequent causes of Mäntsälä GIC > 30 A events. Forward shocks were the third most frequent cause of the > 30 A events. Shock-related GICs were observed to occur at all local times.
The two “Halloween” superstorms of **29–30 and 30–31 October 2003** produced by far the greatest number of GICs in the interval of study (9 > 30 A GICs and 168 > 10 A GICs). In the first Halloween superstorm, a shock-triggered SSS (SML < −3548 nT) caused 33, 57, 51 and 52 A GICs. The 57 A GIC was the most intense event of the superstorm and of this study. It is possible that this SSS is a new form of substorm. Equally intense magnetic storms were also studied but their related GICs were far less numerous and less intense.

Space weather explorer – The KuaFu mission

C.-Y. **Tu**, R. Schwenn[b], E. Donovan[c], E. Marsch[b], J.-S. Wang[d], L.-D. Xia[e], , Y.-W. Zhang[f] and on behalf of the KuaFu working team
Advances in Space Research
Volume 41, Issue 1, 2008, Pages 190-209

The KuaFu mission is designed to explore the physical processes that are responsible for space weather, complementing planned in situ and ground-based programs, and also to make an essential contribution to the space weather application. KuaFu encompasses three spacecraft. KuaFu-A will be located at the L1 libration point and have instruments to observe solar extreme ultraviolet (EUV) and far ultraviolet (FUV) emissions and white-light coronal mass ejections (CMEs), and to measure radio waves, the local plasma and magnetic field, and high-energy particles. KuaFu-B1 and KuaFu-B2 will be in elliptical polar orbits chosen to facilitate continuous (24 h per day 7 days per week) observation of the northern polar aurora oval and the inner magnetosphere. The KuaFu mission is designed to observe globally the complete chain of disturbances from the solar atmosphere to geospace, including solar flares, CMEs, interplanetary clouds, shock waves, and their geo-effects, with a particular focus on dramatic space weather events such as magnetospheric substorms and magnetic storms. The mission start is targeted for the next solar maximum with launch hoped for in 2012. The initial mission lifetime will be 3 years. The overall mission design, instrument complement, and incorporation of recent technologies will advance our understanding of the physical processes underlying space weather, solve several key outstanding questions including solar CME initiation, Earth magnetic storm and substorm mechanisms, and advance our understanding of multi-scale interactions in and system-level behavior of our Sun–Earth space plasma system.

Upgrade of GLE database: Assessment of effective dose rate at flight altitude

S.Tuohino, A.IbragimovbI.UsoskincdA.Mishev

Advances in Space Research Volume 62, Issue 2, 15 July **2018**, Pages 398-407
http://sci-hub.tw/http://linkinghub.elsevier.com/retrieve/pii/S0273117718303363

A new database for assessment of radiation doses at cruise flight altitude in the Earth atmosphere, related to ground level enhancement (GLE) events is created under VarSiTi/SCOSTEP support and incorporated to the International ground level enhancement (GLE) database (gle.oulu.fi). The upgraded database provides, for each GLE event, where possible, information on the estimated energy/rigidity spectra of solar energetic particles and the corresponding computed effective doses at cruise flight altitude of 35 kft (10,668 m above sea level). The computations are performed for various reconstructions of solar energetic particles spectra, available in literature, thus for some events there are several results. Computations were performed using a recent model for assessment of effective dose due to cosmic ray particles, applied specifically in the polar region, where the exposure is maximal. This upgrade allows one to estimate the radiation effects at cruise flight altitude caused by major GLE events over several decades.

National Response to a Severe Space Weather Event

Turner, Ronald

Space Weather, Vol. 10, No. 3, S03008, **2012**
http://dx.doi.org/10.1029/2011SW00075

Introduction to the policy structure in place to coordinate nationwide preparation for and response to a space weather event of national scope and impact.

The effects of space weather, while disruptive and potentially costly, are generally limited in scope, as described by NOAA's Space Weather Scales (http://www.swpc.noaa.gov/NOAAscales/). However, as a recent National Research Council (NRC) workshop report notes, severe space weather can have significant societal and economic impacts [NRC, 2008], including regional power outages [Kappenman, 2010], damage to satellites [Odenwald et al., 2006], and degradation of service provided by space-based systems (primarily navigation and communication) [NRC, 2008]. Over the past few years, there has been increasing governmental concern about the prospect of an epic space weather event that could cause widespread damage with long-lasting effects [National Defense University, 2011; Holdren and Beddington, 2011; U.S. Federal Emergency Management Agency et al., 2010]. In the spring of 2012, Florida's Division of Emergency Management will conduct a series of exercises focused on the potential impacts of a geomagnetic storm [Florida Division of Emergency Management, 2011]. These exercises will be used as a model for similar operations in other regions.

An improved forecast system for relativistic electrons at geosynchronous orbit

Turner, D. L.; Li, X.; Burin des Roziers, E.; Monk, S.

Space Weather, Vol. 9, No. 6, S06003, **2011**
http://dx.doi.org/10.1029/2010SW000647

Here we provide a review of existing forecast models for Earth's outer radiation belt electrons, discuss some recent improvements to two of these models, and present a new and improved forecast system for relativistic electrons at GEO. For the first time, we can forecast at a local hour resolution around GEO using a statistical tool included in the system. This forecast system also includes several real-time forecast models, two previously existing and one that is a new development. This new model incorporates an internal electron source, simulating local acceleration by wave-particle interactions, and it proves to be the most accurate of the models in the system. For 2007–2008, it achieves +1 and +2 day prediction efficiencies of 0.90 and 0.63. We conclude this work with a discussion of how these models are currently operational and providing results to the community online in real time, and we also speculate on future possibilities to allow for forecasts with extended lead times and ranges throughout the rest of the outer radiation belt.

Solar Cycle Slow to Get Going: What Does It Mean for Space Weather?

Turner, Ronald

Space Weather, Vol. 9, No. 4, S04004, **2011**

If you have the sense that the current solar cycle has been slow to build up, maybe it is more than just the "watched pot" failing to boil. A comparison with previous sunspot cycles shows that the current cycle is among the slowest-growing cycles characterized with good historical data. Figure 1 shows the smoothed sunspot number for the period from 2 years before the minimum to 2 years after it for the 24 numbered solar cycles (cycle 1 started in 1755; we are just now entering cycle 24). It illustrates the historically slow increase of the current cycle (shown in red) as of February 2011. Three of the four cycles with slower increases (shown in blue) were during the Dalton Minimum in the early nineteenth century. The fourth is the period leading into cycle 1. The red dots in the figure are cycle 24 monthly average sunspot numbers; these data are too recent to be adjusted by the smoothing algorithm that includes the influence of monthly averages within 6 months of the smoothed value. Also shown, at the bottom of the figure, for context, are the sunspot data for the first 23 cycles, which also identify the Dalton Minimum.

Radiation dose during relativistic electron precipitation events at the International Space Station

H. **Ueno** , S. Nakahira , R. Kataoka, Y. Asaoka, S. Torii , S. Ozawa, H. Matsumoto , A. Bruno , G.A. de Nolfo, G. Collazuol , S.B. Ricciarini

Space Weather **2019**

sci-hub.se/10.1029/2019SW002280

We provide a quantitative estimate of the radiation dose during relativistic electron precipitation (REP) events at the International Space Station (ISS). To this goal, we take advantage of the data collected by the CALorimetric Electron Telescope (CALET), the Monitor of All-sky X-ray Image (MAXI), and the Space Environment Data Acquisition equipment – Attached Payload (SEDA-AP). The three ISS detectors offer complementary REP observations, including energy spectra and flux directional information, during a period of approximately two and a half years, from November 2015 to March 2018. We have identified 762 REP events during this period from which we obtain the distribution of radiation dose, relevant to extravehicular activities outside the International Space Station (ISS).

Global geomagnetic perturbation forecasting using Deep Learning

Vishal **Upendran**, Panagiotis Tigas, Banafsheh Ferdousi, Teo Bloch, Mark C. M. Cheung, Siddha Ganju, Asti Bhatt, Ryan M. McGranaghan, Yarin Gal

Space Weather **2022**

https://arxiv.org/pdf/2205.12734.pdf

Geomagnetically Induced Currents (GICs) arise from spatio-temporal changes to Earth's magnetic field which arise from the interaction of the solar wind with Earth's magnetosphere, and drive catastrophic destruction to our technologically dependent society. Hence, computational models to forecast GICs globally with large forecast horizon, high spatial resolution and temporal cadence are of increasing importance to perform prompt necessary mitigation. Since GIC data is proprietary, the time variability of horizontal component of the magnetic field perturbation (dB/dt) is used as a proxy for GICs. In this work, we develop a fast, global dB/dt forecasting model, which forecasts 30 minutes into the future using only solar wind measurements as input. The model summarizes 2 hours of solar wind measurement using a Gated Recurrent Unit, and generates forecasts of coefficients which are folded with a spherical harmonic basis to enable global forecasts. When deployed, our model produces results in under a second, and generates global forecasts for horizontal magnetic perturbation components at 1-minute cadence. We evaluate our model across models in literature for two specific storms of **5 August 2011** and **17 March 2015**, while having a self-consistent benchmark model set. Our model outperforms, or has consistent performance with state-of-the-practice high time cadence local and low time cadence global models, while also outperforming/having comparable performance with the benchmark models. Such quick inferences at high temporal cadence and arbitrary spatial resolutions may ultimately enable accurate forewarning of dB/dt for any place on Earth, resulting in precautionary measures to be taken in an informed manner.

A new database of radiation doses at commercial flight altitudes due to solar particle storms is linked to GLE database

I. **Usoskin**1, 2, A. Mishev1, 2, S. Tuohino1, and A. Ibragimov

VarSITI Newsletter Vol. 16, January **2018** Article 1

http://newserver.stil.bas.bg/varsiti/newsL/VarSITI_Newsletter_Vol16.pdf

Links of Terrestrial Volcanic Eruptions to Solar Activity and Solar Magnetic Field

Vasilieva Irina & Zharkova Valentina

Global Journal of Science Frontier Research: A Physics and Space Science Volume 23 Issue 3 Version 1.0 Year **2023**

https://globaljournals.org/GJSFR_Volume23/2-Links-of-Terrestrial-Volcanic.pdf

We compare frequencies of volcanic eruptions (VEs) in the past 270 years with variations of solar activity and summary curve of eigen vectors (EVs) of the solar background magnetic field (SBMF) from the WSO synoptic magnetic maps. In the period 1868 - 1950 and 1990-2020 the total numbers of volcanic eruptions are maximal during the maxima or the descending phase of the magnetic field cycles with the dominant southern polarity, and minimal during the maxima or ascending phase of the magnetic field cycles with the northern polarity. While in the earlier years (1762-1868) this link disappeared. The frequency analysis of VEs with Morlet wavelet reveals the dominant period of about 22 years and weaker periods of 10.7 and 55-70 years. Comparison of VE frequencies with the modulus summary curve (MSC) of EVs of SBMF for solar cycles after 1868 reveals a strong positive correlation (coefficient of 0.84) with the maxima of VEs occurring when the summary curve of EVs derived from the solar magnetic fields have the southern polarity, or more active southern hemisphere of the Sun, and minima when the northern one.

Terrestrial volcanic eruptions and their association with solar activity

I. **Vasilieva**, V. Zharkova

ApJ 2022

https://arxiv.org/pdf/2203.03637.pdf

https://solargsm.com/wp-content/uploads/2022/07/vasilieva_zharkova_volcanos.pdf

Frequencies of volcanic eruptions in the past 270 years are compared with variations of solar activity and summary curve of principal components of the solar background magnetic field (SBMF).Frequency analysis with Morlet wavelet reveals the most pronounced period of volcanic eruptions of 22 years. There is a strong correlation (-0.84) between volcanic frequencies and the summary curve of SBMF for 11 cycles after 1868. The maxima of volcanic eruptions are shown to occur during solar activity cycles with the southern magnetic polarity. The next anticipated maximum of volcanic eruptions is expected to occur during cycle 26, when SBMF have a southern magnetic polarity.

Cosmic radiation and its effects on technology and health

I. **Vavitsas**1,2,a) and K. Kalachanis2

AIP Conference Proceedings 2075, 200018 (**2019**);

https://doi.org/10.1063/1.5099028

http://aip.scitation.org/doi/pdf/10.1063/1.5099028

In ancient Greece the observations of the famous doctor Hippocrates of Kos had shown proved theenvironmental impact on human health. Although the term “environment” should not only include the nature surroundingus but also space since the evolution of life depends primarily on events such supernova explosions, formation of starsand falls of meteorites. A major factor in life sustainment is also cosmic radiation, originating from supernova star explosions, γ-ray bursts and cosmic background radiation and has a major impact both on human health and technology.

Equatorial coronal holes, solar wind high-speed streams, and their geoeffectiveness_

G. **Verbanac**1, B. Vršnak2, A. Veronig3, and M. Temmer3

A&A 526, A20 (**2011**), **File**

Context.Solar wind high-speed streams (HSSs), originating in equatorial coronal holes (CHs), are the main driver of the geomagnetic activity in the late-declining phase of the solar cycle.

Aims.We analyze correlations between CH characteristics, HSSs parameters, and the geomagnetic activity indices, to establish empirical relationships that would provide forecasting of the solar wind characteristics, as well as the effect of HSSs on the geomagnetic activity in periods when the effect of coronal mass ejections is low.

Methods.We apply the cross-correlation analysis to the fractional CH area (*CH*) measured between central meridian distances ±10◦, solar wind parameters (flow velocity *V*, proton density *n*, temperature *T*, and the magnetic field *B*), and the geomagnetic indices *Dst* and *Ap*.

Results. The cross-correlation analysis reveals a high degree of correlation between all studied parameters. In particular, we show that the *Ap* index is considerably more sensitive to HSS and CH characteristics than *Dst*. The *Ap* and *Dst* indices are most tightly correlated with the solar wind parameter *BV*2.

Conclusions.From the point of view of space weather, the most important result is that the established empirical relationships provide a few-days-in-advance forecasting of the HSS characteristics and the related geomagnetic activity at the six-hour resolution.

Addressing Gaps in Space Weather Operations and Understanding with Small Satellites

Olga Verkhoglyadova, Charles Bussy-Virat, Amir Caspi, David Jackson, Vladimir Kalegaev, Jeffrey Klenzing, Jesus Nieves-Chinchilla, Angelos Vourlidas

Space Weather **Volume19, Issue3** e2020SW002566 **2020**

https://arxiv.org/ftp/arxiv/papers/2012/2012.03343.pdf
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020SW002566
Gaps in space weather observations that can be addressed with small satellites are identified. Potential improvements in solar inputs to space weather models, space radiation control, estimations of energy budget of the upper Earth's atmosphere, and satellite drag modeling are briefly discussed. Key observables, instruments and observation strategies by small satellites are recommended. Tracking optimization for small satellites is proposed.

Ground-based Observations of the Solar Sources of Space Weather (Invited Review)

Astrid M. **Veronig**, Werner Pötzi

"Ground-based Solar Observations in the Space Instrumentation Era", Proceedings of the Coimbra Solar Physics Meeting 2015, ASP Conference Series, Eds. I. Dorotovic, C. Fischer, and M. Temmer; **2016**

http://arxiv.org/pdf/1602.02721v1.pdf
http://aspbooks.org/publications/504/247.pdf
Monitoring of the Sun and its activity is a task of growing importance in the frame of space weather research and awareness. Major space weather disturbances at Earth have their origin in energetic outbursts from the Sun: solar flares, coronal mass ejections and associated solar energetic particles. In this review we discuss the importance and complementarity of ground-based and space-based observations for space weather studies. The main focus is drawn on ground-based observations in the visible range of the spectrum, in particular in the diagnostically manifold Hα spectral line, which enables us to detect and study solar flares, filaments, filament eruptions, and Moreton waves. Existing Hα networks such as the GONG and the Global High-Resolution Hα Network are discussed. As an example of solar observations from space weather research to operations, we present the system of real-time detection of Hα flares and filaments established at Kanzelh\"ohe Observatory (KSO; Austria) in the frame of the ESA Space Situational Awareness programme. During the evaluation period 7/2013 - 11/2015, KSO provided 3020 hours of real-time Hα observations at the SWE portal. In total, 824 Hα flares were detected and classified by the real-time detection system, including 174 events of Hα importance class 1 and larger. For the total sample of events, 95\% of the automatically determined flare peak times lie within ±5 min of the values given in the official optical flares reports (by NOAA and KSO), and 76\% of the start times. The heliographic positions determined are better than ±5∘. The probability of detection of flares of importance 1 or larger is 95\%, with a false alarm rate of 16\%. These numbers confirm the high potential of automatic flare detection and alerting from ground-based observatories.
August 22, 2015, February 11, 2015

Geomagnetically induced currents in Europe
Modelled occurrence in a continent-wide power grid

Ari **Viljanen**1*, Risto Pirjola1,2, Ernö Prácser3, Juri Katkalov4 and Magnus Wi
J. Space Weather Space Clim. 4 (**2014**) A09
Statistics of geomagnetically induced currents (GIC) in the European high-voltage power grids based on 1-min geomagnetic recordings in 1996–2008 and on 1-D models of the ground conductivity have been derived in the EURISGIC project (European Risk from Geomagnetically Induced Currents). The simplified yet realistic power grid model indicates that large GIC can occur anywhere in Europe. However, geomagnetic variations are clearly larger in North Europe, so it is the likely region of significant GIC events. Additionally, there are areas in the North with especially low ground conductivities, which further tend to increase GIC. The largest modelled GIC values at single substations in 1996–2008 are about 400 A in the Nordic Countries, about 100 A in the British Isles, about 80 A in the Baltic Countries, and less than 50 A in Central and South Europe. The largest GIC event in the period studied is the Halloween storm on 29–30 October 2003, and the next largest ones occurred on 15 July 2000 and 9 November 2004.

European Project to Improve Models of Geomagnetically Induced Currents

Viljanen, Ari
Space Weather, Vol. 9, No. 7, S07007, **2011**
Geomagnetically induced currents (GICs) from solar storms pose a risk to the operation of power transmission grids in Europe and across the globe. The European Risk from Geomagnetically Induced Currents (EURISGIC) project, which began in March 2011 and is supported by the Seventh Framework Programme of the European Union, seeks to mitigate this natural hazard by developing European capabilities for GIC forecasting and warning. Recent well-recognized GIC events were the province-wide blackout in Quebec, Canada, in March 1989 and the blackout in the city of Malmö, in southern Sweden, during the Halloween storm of October 2003. The progressive integration of interconnected and geographically wide power transmission grids is obviously increasing the GIC risk. Hence, there is a need for greater scientific understanding of phenomena in the solar-terrestrial environment that lead to GICs and for the development of systems that facilitate GIC modeling, forecasting, and mitigation.

Improving the Medium-Term Forecasting of Space Weather: A Big Picture Review from a Solar Observer's Perspective Review

Angelos **Vourlidas**
Front. Astron. Space Sci., 8:651527. **2021 |**
https://doi.org/10.3389/fspas.2021.651527
https://www.frontiersin.org/articles/10.3389/fspas.2021.651527/full
We have improved considerably our scientific understanding of the key solar drivers of Space Weather, i.e., Coronal Mass Ejections, flares, in the last 20+ years thanks to a plethora of space missions and modeling advances. Yet, a major breakthrough in assessing the geo-effectiveness of a given CME and associated phenomena still escapes us, holding back actionable medium-term (up to 7 days) forecasting of Space Weather. Why is that? I adopt a two-pronged approach to search for answers. First, I assess the last 20+ years of research on solar drivers by identifying lessons-learned and paradigm shifts in our view of solar activity, always in relation to Space Weather concerns. Then, I review the state of key observation-based quantities used in forecasting to isolate the choke points and research gaps that limit medium-term forecasting performance. Finally, I outline a path forward along three vectors—breakthrough capabilities, geo-effective potential, and actionable forecast—with the strongest potential to improve space weather forecasting horizon and robustness. **2013-11-01, 29 November, 2020**

The Science Case for the 4π Perspective: A Polar/Global View for Studying the Evolution & Propagation of the Solar Wind and Solar Transients **mini-Review**
A. **Vourlidas**, S. Gibson, D. Hassler, T. Hoeksema, M. Linton, N. Lugaz, J. Newmark
White Paper submitted to the Heliophysics 2050 Workshop **2020**
https://arxiv.org/ftp/arxiv/papers/2009/2009.04880.pdf
To make progress on the open questions on CME/CIR propagation, their interactions and the role and nature of the ambient solar wind, we need spatially resolved coverage of the inner heliosphere -- both in-situ and (critically) imaging -- at temporal scales matching the evolutionary timescales of these phenomena (tens of minutes to hours), and from multiple vantage points. The polar vantage is uniquely beneficial because of the wide coverage and unique perspective it provides. The ultimate goal is to achieve full 4π coverage of the solar surface and atmosphere by 2050.

Radio Observations of Coronal Mass Ejections: Space Weather Aspects **Review**
Angelos **Vourlidas** , Eoin P Carley and Nicole Vilmer
Front. Astron. Space Sci. **2020**
doi: 10.3389/fspas.2020.00043
We review the current state-of-affairs in radio observations of Coronal Mass Ejections (CMEs) from a Space Weather perspective. In particular, we examine the role of radio observations in predicting or presaging an eruption, in capturing the formation stages of the CME, and in following the CME evolution in the corona and heliosphere. We then look to the future and identify capabilities and research areas where radio observations---particularly, spectropolarimetric imaging---offer unique advantages for Space Weather research on CMEs. We close with a discussion of open issues and possible strategies for enhancing the relevance and importance of radio astronomy for Space Weather science.

Predicting the geoeffective properties of coronal mass ejections: current status, open issues and path forward **Review**
A. **Vourlidas**, S. Patsourakos, and N. P. Savani
Philosophical Transactions of the Royal Society A v. 377 Issue 2148 Article ID:20180096 **2019 File**
https://royalsocietypublishing.org/doi/pdf/10.1098/rsta.2018.0096
Much progress has been made in the study of coronal mass ejections (CMEs), the main drivers of terrestrial space weather thanks to the deployment of several missions in the last decade. The flow of energy required to power solar eruptions is beginning to be understood. The initiation of CMEs is routinely observed with cadences of tens of seconds with arc-second resolution. Their inner heliospheric evolution can now be imaged and followed routinely. Yet relatively little progress has been made in predicting the geoeffectiveness of a particular CME. Why is that? What are the issues holding back progress in medium-term forecasting of space weather? To answer these questions, we review, here, the measurements, status and open issues on the main CME geoeffective parameters; namely, their entrained magnetic field strength and configuration, their Earth arrival time and speed, and their mass (momentum). We offer strategies for improving the accuracy of the measurements and their forecasting in the near and mid-term future. To spark further discussion, we incorporate our suggestions into a top-level draft action plan that includes suggestions for sensor deployment, technology development and modelling/theory improvements.
2. Forecasting coronal mass ejection time of arrivals and speeds at 1 AU
(a) Empirical models (b) Drag-based models (c) Shock-based models (d) Magnetohydrodynamic models (e) Machine learning (f) Assessment of time-of-arrival studies (g) Hit/miss (h) What limits the accuracy of coronal mass ejection arrival prediction? (i) Path forward
3. Forecasting coronal mass ejection mass at 1 AU

(a) State-of-the-art (b) Issues and path forward
4. Forecasting coronal mass ejection size at 1 AU
(a) State-of-the-art (b) Issues and path forward
5. Forecasting coronal mass ejection magnetic fields at 1 AU
(a) Decomposing the *Bz* problem (b) The magnitude of the magnetic field (c) Empirical models (d) Why is difficult to predict *Bz*? (e) Path forward

EUV Irradiance Inputs to Thermospheric Density Models: Open Issues and Path Forward

A. **Vourlidas**, S. Bruinsma
Space Weather Vol: 16, Pages: 5–15 **2018**
https://arxiv.org/ftp/arxiv/papers/1801/1801.06092.pdf
http://sci-hub.tw/10.1002/2017SW001725

One of the objectives of the NASA LWS Institute on Nowcasting of Atmospheric Drag for LEO Spacecraft was to investigate whether and how to increase the accuracy of atmospheric drag models by improving the quality of the solar forcing inputs, namely Extreme Ultraviolet (EUV) irradiance information. In this focused review, we examine the status of and issues with EUV measurements and proxies, discuss recent promising developments, and suggest a number of ways to improve the reliability, availability, and forecast accuracy of EUV measurements in the next solar cycle.

Mission to the Sun-Earth L5 Lagrangian Point: An Optimal Platform for Space Weather Research

Angelos **Vourlidas**
Space Weather Volume 13, Issue 4 April **2015** Pages 197–201
Space Weather Quarterly Vol. 12, Issue 2, pp. 9-13, **2015**
http://onlinelibrary.wiley.com/doi/10.1002/SWQv12i002/epdf

The Sun-Earth Lagrangian L5 point is a uniquely advantageous location for space weather research and monitoring. It covers the “birth-to-impact” travel of solar transients; it enables imaging of solar activity at least 3 days prior to a terrestrial viewpoint and measures the solar wind conditions 4–5 days ahead of Earth impact. These observations, especially behind east limb magnetograms, will be a boon for background solar wind models, which are essential for coronal mass ejection (CME) and shock propagation forecasting. From an operational perspective, the L5 orbit is the space weather equivalent to the geosynchronous orbit for weather satellites. Optimal for both research and monitoring, an L5 mission is ideal for developing a Research-to-Operations capability in Heliophysics.

Analytical and empirical modelling of the origin and heliospheric propagation of coronal mass ejections, and space weather applications **Review**

Bojan **Vršnak***
J. Space Weather Space Clim. **2021**, 11, 34
https://www.swsc-journal.org/articles/swsc/pdf/2021/01/swsc200091.pdf
https://doi.org/10.1051/swsc/2021012

The focus is on the physical background and comprehension of the origin and the heliospheric propagation of interplanetary coronal mass ejections (ICMEs), which can cause most severe geomagnetic disturbances. The paper considers mainly the analytical modelling, providing useful insight into the nature of ICMEs, complementary to that provided by numerical MHD models. It is concentrated on physical processes related to the origin of CMEs at the Sun, their heliospheric propagation, up to the effects causing geomagnetic perturbations. Finally, several analytical and statistical forecasting tools for space weather applications are described. **November 3, 1997**

Statistical Analysis of the Correlation Between Anomalies in the Czech Electric Power Grid and Geomagnetic Activity

Tatiana **Výbošťoková**, Michal Švanda
Space Weather Quarterly Volume 16, Issue 4, p. 5-15, **2019**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/swq.24

Comparative Accuracies of Models for Drag Prediction During Geomagnetically Disturbed Periods: A First Principles Model Versus Empirical Models

R. L. **Walterscheid**, M. W. Chen, C.-C. Chao, S. Gegenheimer, J. Cabrera-Guzman, J. McVey
Space Weather e2022SW003332 Volume21, Issue5 **2023**
https://doi.org/10.1029/2022SW003332

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022SW003332
We examine the accuracy of density prediction by the first principles model Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM) developed by the National Center for Atmospheric Research and compare it to the accuracy of three empirical models: Jacchia 71, the Naval Research Laboratory Mass Spectrometer Incoherent Scatter Extended 2000 (NRLMSIS), Jacchia 1971, and Jacchia-Bowman 2008. Comparisons are made for three large storms: the October 2003 storm, the March 2013 storm, and the March 2015 storm. To evaluate the accuracy of these models we use tracking data for nine space objects in low Earth orbit. Additionally, we evaluate the accuracy of the TIEGCM and NRLMSIS with data from high precision accelerometers on the Challenging Minisatellite Payload (CHAMP) and Gravity field and Circulation Explorer (GOCE) satellites. The goal is to assess the use of a first principles model as a potential tool for forecasting satellite drag during large magnetic storms. For the storms considered, we found the TIEGCM, JB2008, and NRLMSIS models to be substantially more accurate than the Jacchia 71 model. The accuracies of the TIEGCM and JB2008 models were similar, but overall, the TIEGCM was more accurate. We found smaller differences for TIEGCM versus CHAMP than for NRLMIS for the Halloween Storm, and smaller differences than results published for JB2008 and the assimilative model HASDM. The empirical models are at present more practical for operational purposes, but the TIEGCM, developed as a research model, with a greater focus on operational use offers the potential for improved utility during stressing conditions. **Oct 28-Nov 4 2003, 17-19 Mar 2012, 16-20 Mar 2015**

Estimates of Spherical Satellite Drag Coefficients in the Upper Thermosphere During Different Geomagnetic Conditions

Xin **Wang**, Tingling Ren, Ronglan Wang, Bingxian Luo, Ercha Aa, Lei Cai, Ming Li, Juan Miao, Siqing Liu, Jiancun Gong
Space Weather Volume22, Issue11 November **2024** e2024SW003974
https://doi.org/10.1029/2024SW003974
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2024SW003974
Satellite drag coefficients are crucial for determining the neutral mass densities that affect spacecraft operations in the thermosphere. Many studies typically utilize a constant drag coefficient of 2.2 to calculate the neutral density. However, due to the variability of space environment, uncertainties in the drag coefficient can lead to significant systematic discrepancies in neutral density measurements. Satellite drag coefficient may fluctuate in the thermosphere under various geomagnetic activities and altitudes. For the first time, we calculate the spherical satellite drag coefficient using data from the "Orbital Atmospheric Density Detection Experimental Satellite," referred to as the QX satellite. Our findings reveal that the drag coefficient can be estimated by thermospheric temperature and density, which are dependent on geomagnetic activity and altitude. At an altitude of ~510 km, drag coefficients are adjusted to around 2.425, instead of the constant value of 2.2. Furthermore, the drag coefficient may decrease due to the significant influence of increasing geomagnetic activity, such as geomagnetic storms, on thermospheric density and temperature. These estimates of the drag coefficient can also be used to reduce discrepancies when deducing the ballistic coefficient. Consequently, using the estimated drag coefficient can accurately determine the QX-derived neutral density, which agrees well with the density from Swarm-B satellite. **28 July–30 September 2022, 16-19 August 2022, 1 October 2022–31 January 2023, 1 February–30 June 2023**

China's Ground-Based Space Environment Monitoring Network—Chinese Meridian Project (CMP)

Chi **Wang**, Jiyao Xu, Zhiqing Chen, Hui Li, Xueshang Feng, Zhaohui Huang, Jiangyan Wang
Space Weather Volume22, Issue7 July **2024** e2024SW003972
https://doi.org/10.1029/2024SW003972
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2024SW003972
Monitoring and investigation of the solar-terrestrial space environment is a huge challenge for humans in space age. To this end, China has established the Ground-based Space Environment Monitoring Network, namely Chinese Meridian Project (CMP). The project comprises three major systems: the Space Environment Monitoring System, Data and Communication System, and Scientific Application System. The Space Environment Monitoring System adopts a well-designed monitoring architecture, known as "One Chain, Three Networks, and Four Focuses," to achieve stereoscopic and comprehensive monitoring of the entire solar-terrestrial space. The "One-Chain" component utilizes optical, radio, interplanetary scintillation, cosmic ray instruments to cover the causal chain of space weather disturbances from the solar surface to near-Earth space. For the ionosphere, middle and upper atmosphere, and magnetic field, instruments are deployed along longitudes of 120° and 100°E, and latitudes of 30° and 40°N, forming the "Three Networks." Furthermore, more powerful monitoring facilities or large-scale instruments have been deployed in four key regions: the high-latitude polar region, mid-latitude region in northern China, low-latitude region at Hainan Island, and the Tibet region. These four regions are crucial for disturbances propagation and evolution, or possess unique geographical and topographical characteristics. The Data and Communication System and Scientific Application System are designed for data collecting, processing, storage, mining, and providing user service based on data acquired by the Space Environment Monitoring System. The data

obtained by CMP will be shared with the global scientific community, facilitating enhanced collaboration on space weather and space physics research.

Contribution of the Chinese Meridian Project to space environment research: Highlights and perspectives. **Review**

Wang, C., Xu, J., Liu, L. et al.

Sci. China Earth Sci. 66, 1423–1438 (**2023**).

https://doi.org/10.1007/s11430-022-1043-3

https://link.springer.com/content/pdf/10.1007/s11430-022-1043-3.pdf

The Chinese Meridian Project (CMP) is devoted to establishing a comprehensive ground-based monitoring network for China's space weather research. CMP is a major national science and technology infrastructure project with the participation of more than 10 research institutions and universities led by the National Space Science Center of the Chinese Academy of Sciences. CMP is planned to be constructed in two phases: CMP phases I and II. The first phase (CMP-I) started construction in 2008 and completed in 2012, after which it entered the operation stage. The 10-year observation of CMP-I has made significant scientific discoveries and achievements in the research fields of the middle and upper atmospheric fluctuations, metal layers in the mesosphere and lower thermosphere, ionospheric disturbances and irregularities, geomagnetic disturbances, and influences of solar activity. The review summarizes the main observations and research achievements, space weather forecast modeling and methods based on CMP-I over the past 10 years, and presents a future extension perspective along with the construction of CMP-II.

Improving Precise Orbit Determination of LEO Satellites Using Enhanced Solar Radiation Pressure Modeling

Youcun **Wang**, Min Li, Kecai Jiang, Wenwen Li, Qile Zhao, Rongxin Fang, Na Wei, Renhai Mu

Space Weather e2022SW003292 Volume21, Issue1 **2023**

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022SW003292

Precise orbit knowledge is a fundamental requirement for low Earth orbit (LEO) satellites. High-precision non-gravitational force modeling directly improves the overall quality of LEO precise orbit determination (POD). To address the potential systematic errors in solar radiation pressure (SRP), we introduce observed radiation data and modeled physical effects to describe the real in-flight environment of satellites. Time-dependent solar irradiance data and a highly physical shadow model are considered for SRP modeling. We develop an advanced thermal reradiation model for satellite solar panels. A set of improved non-gravitational force models is performed for LEO POD, and we discuss the benefits of the enhanced dynamic models on orbit quality and dependence on empirical parameters. The Gravity Recovery and Climate Experiment Follow-On (GRACE-FO), Jason-3, and Haiyang-2B missions are selected for the POD process. Estimated empirical acceleration and scale parameters and independent satellite laser ranging (SLR) are used to validate the final orbit solutions. The magnitude of empirical acceleration estimated in POD is reduced by 19% with the enhanced dynamic modeling, and the estimated scale factor for the SRP converges to stable and reasonable level. Furthermore, the steady-state temperature model used in thermal reradiation can effectively reduce mismodeled effects in the SRP, and the systematic linear dependency revealed by the SLR residuals is significantly reduced for the GRACE-C and Jason-3 satellites, with improvements of approximately 61% and 49%, respectively. Overall, advances are made in the explicit modeling of non-gravitational forces to pursue superior satellite orbits, suggesting a more dynamic orbit solution.

Medium Range Forecasting of Solar-Wind: A Case Study of Building Regression Model with Space Weather Forecast Testbed (SWFT)

Chunming **Wang**, I. Gary Rosen, Bruce T. Tsurutani, Olga P. Verkhoglyadova, Xing Meng, Anthony J. Mannucci

Space Weather e2019SW002433 **2020**

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019SW002433

The Space Weather Forecast Testbed (SWFT) is developed by a team of space weather scientists and mathematicians at the University of Southern California (USC) and Jet Propulsion Laboratory (JPL) to foster the creation of models for space weather forecast by exploration of existing historic data using techniques of machine-learning. As an example to demonstrate the potential power of SWFT, we present in this paper a multilinear regression based forecast model for solar wind. Solar wind is one of the key drivers for numerous physics-based models for space weather including thermosphere and ionosphere models. Many attempts have been made to produce forecasts for the solar wind. SWFT provides an unified framework for forecast model formulation, training and performance assessment. In particular, the preparation of training and validation data by SWFT takes into account of realistic constraints on data latency and forecast lead time. In developing a solar wind forecast model, SWFT allows fast exploration of many meta-parameters such as the list of predictive variables and their time history used in constructing a model. We present the impact of meta-parameter selection, as well as, performance relative to existing solar wind forecast models. **May 1st, 2011**.

Solar 11-Year Cycle Signal in Stratospheric Nitrogen Dioxide—Similarities and Discrepancies Between Model and NDACC Observations

Shuhui **Wang**, King-Fai Li, Diana Zhu, Stanley P. Sander, Yuk L. Yung, Andrea Pazmino & Richard Querel

Solar Physics volume 295, Article number: 117 (**2020**)

https://link.springer.com/content/pdf/10.1007/s11207-020-01685-1.pdf

NOx (NO2 and NO) plays an important role in controlling stratospheric ozone. Understanding the change in stratospheric NOx and its global pattern is important for predicting future changes in ozone and the corresponding implications on the climate. Stratospheric NOx is mainly produced by the reaction of N2O with the photochemically produced O(1D) and, therefore, it is expected to vary with changes in solar UV irradiance during the solar cycle. Previous studies on this topic, often limited by the relatively short continuous data, show puzzling results. The effect of the 1991 Pinatubo eruption might have caused interference in the data analysis. In this study, we examine the NO2 vertical column density (VCD) data from the Network for the Detection of Atmospheric Composition Change (NDACC). Data collected at 16 stations with continuous long-term observations covering the most recent Solar Cycles 23 and 24 were analyzed. We found positive correlations between changes in NO2 VCD and solar Lyman-αα over nine stations (mostly in the Northern Hemisphere) and negative correlations over three stations (mostly in the Southern Hemisphere). The other four stations do not show significant NO2 solar-cycle signal. The varying NO2 responses from one location to another are likely due to different geo-locations (latitude and altitude). In particular, two high-altitude stations show the strongest positive NO2 solar-cycle signals. Our 1D chemical-transport model calculations help explain the altitude dependence of NO2 response to the solar cycle. NO2 solar-cycle variability is suggested to play an important role controlling O3 at an altitude range from ≈20 km≈20 km to near 60 km, while OH solar-cycle variability controls O3 at 40 – 90 km. While observations show both positive and negative NO2 responses to solar forcing, the 1D model predicts negative NO2 responses to solar UV changes throughout the middle atmosphere. 3D global model results suggest complex roles of dynamics in addition to photochemistry. The energetic particle-induced NO2 variabilities could also contribute significantly to the NO2 variability during solar cycles.

CME Arrival Time Prediction Using Convolutional Neural Network

Yimin **Wang**1,2, Jiajia Liu1, Ye Jiang3, and Robert Erdélyi1,4

2019 ApJ 881 15

sci-hub.se/10.3847/1538-4357/ab2b3e

Fast and accurate prediction of the arrival time of coronal mass ejections (CMEs) at Earth is vital to minimize hazards caused by CMEs. In this paper, we use a deep-learning framework, i.e., a convolutional neural network (CNN) regression model, to analyze transit times from the Sun to Earth of 223 geoeffective CME events observed in the past 30 yr. 90% of them were used to build the prediction model, and the rest 10% have been used for test purpose. Unlike previous studies on this topic, our proposed CNN regression model does not require manually selected features for model training, it does not need time spent on feature collection, and it can deliver predictions without deeper expert knowledge. The only input to our CNN regression model is the instances of the white-light observations of CMEs. The mean absolute error of the constructed CNN regression model is about 12.4 hr, which is comparable to the average performance of the previous studies on this subject. As more CME data become available, we expect the CNN regression model will reveal better results.

An operational solar wind prediction system transitioning fundamental science to operations

Jingjing **Wang**1*, Xianzhi Ao1, Yuming Wang2, Chuanbing Wang2, Yanxia Cai1, Bingxian Luo1,3, Siqing Liu1,3, Chenglong Shen2, Bin Zhuang2, Xianghui Xue2 and Jiancun Gong1

J. Space Weather Space Clim. Volume 8, **2018** A39

https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc170037.pdf

We present in this paper an operational solar wind prediction system. The system is an outcome of the collaborative efforts between scientists in research communities and forecasters at Space Environment Prediction Center (SEPC) in China. This system is mainly composed of three modules: (1) a photospheric magnetic field extrapolation module,

along with the Wang-Sheeley-Arge (WSA) empirical method, to obtain the background solar wind speed and the magnetic field strength on the source surface; (2) a modified Hakamada-Akasofu-Fry (HAF) kinematic module for simulating the propagation of solar wind structures in the interplanetary space; and (3) a coronal mass ejection (CME) detection module, which derives CME parameters using the ice-cream cone model based on coronagraph images. By bridging the gap between fundamental science and operational requirements, our system is finally capable of predicting solar wind conditions near Earth, especially the arrival times of the co-rotating interaction regions (CIRs) and CMEs. Our test against historical solar wind data from 2007 to 2016 shows that the hit rate (HR) of the high-speed enhancements (HSEs) is 0.60 and the false alarm rate (FAR) is 0.30. The mean error (ME) and the mean absolute error (MAE) of the maximum speed for the same period are −73.9 km s−1 and 101.2 km s−1, respectively. Meanwhile, the ME and MAE of the arrival time of the maximum speed are 0.15 days and 1.27 days, respectively. There are 25 CMEs simulated and the MAE of the arrival time is 18.0 h. **April 18, 2014, n June 22, 2015**
Table 1. Information list of the CMEs along with the auto-detection results (2014-2016)
Table 2. CME parameters and arrival time prediction

What Is a Solar Electromagnetic Storm?

Wang, H., G. Ai, and J. Wang
(**2012**), Space Weather, 10, S09003, doi:10.1029/2012SW000847**. File**
In recent years, the expression “solar storm” has become popular in China, but many Chinese do not realize that solar storms are very different from storms on Earth. As solar physicists and members of the Regional Warning Center China (RWCC) of International Space Environment Services (ISES), we frequently encounter the question “What is a solar storm?” In order to properly respond to the customers of the RWCC, we investigated the historical evolution of the term “solar storm.”

New Chains of Space Weather Monitoring Stations in China,

Wang, C.,
Space Weather, 8, S08001, doi:10.1029/2010SW000603, (**2010**).
(Полученный журнал Space Weather (Quarterly), Vol. 7, No. 3, pp.10-13, 2010)
To develop an understanding of near-Earth space's response to solar activities and to eventually enhance the success of space weather predictions, it is crucial to make synergetic observations of the entire environment from the Sun to the Earth as a system. Since the beginning of the space era, direct observations by satellites have become a much needed means toward this end. However, ground-based observations also have advantages and serve as a counterpart to those made in space. For example, instruments on the ground are much less expensive and easier to repair than those on satellites. Ground-based observations provide continuous high-resolution data not subject to the limitation of the downlink data rate from satellites to ground receiving stations. Also, because some observations have been made from Earth for hundreds of years, society has long and continuous records of quantities such as geomagnetic field variations, measurements of relative ionospheric opacity, and sunspot observations. Data from spacecraft, on the other hand, go back only a few decades.

The application of radio diagnostics to the study of the solar drivers of space weather

Warmuth, A., & Mann, G.:
Springer Lecture Notes in Physics, Vol. 656, 49, **2005; File**

Linear forecasting of the F10.7 proxy for solar activity

Harry P. **Warren**, John T. Emmert, Nicholas A. Crump
Space Weather Volume 15, Issue 8 August **2017** Pages 1039–1051
http://sci-hub.cc/10.1002/2017SW001637
The ability to accurately forecast variations in the solar extreme ultraviolet irradiance is important to many aspects of operational space weather. For example, variations in the Sun's radiative output at these wavelengths drive changes in thermospheric density, which perturbs the trajectories of objects in low Earth orbit. Thus, predicting the conjunction of an operational satellite with orbital debris requires accurate forecasts of solar activity. In this paper we present a simple linear forecasting model for the 10.7 cm radio flux ($F_{10.7}$), a commonly used proxy for solar activity. Comparisons with simple reference models indicate that this linear model has positive skill for all forecast days that we have considered. We also examine the impact of the $F_{10.7}$ forecast skill on empirical model predictions of thermospheric density and ionospheric total electron content.

Analysis of Large Geomagnetically Induced Currents During the 7-8 September 2017 Storm: Geoelectric Field Mapping

Anna **Wawrzaszek** (1), Agnieszka Gil (1 and 2), Renata Modzelewska (2), Bruce T. Tsurutani (3), Roman Wawrzaszek (1)
Space Weather e2022SW003383 **Volume21, Issue3** **2023**

https://arxiv.org/pdf/2302.11699
https://doi.org/10.1029/2022SW003383
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022SW003383
High temporal and high spatial resolution geoelectric field models of two Mäntsälä, Finnish pipeline GIC intervals that occurred within the 7-8 September, 2017 geomagnetic storm have been made. The geomagnetic measurements with 10 s sampling rate of 28 IMAGE ground magnetometers distributed over the north Europe (from 52.07∘ to 69.76∘ latitude) are the bases for the study. A GeoElectric Dynamic Mapping (GEDMap) code was developed for this task. GEDMap considers 4 different methods of interpolation and allows a grid of 0.05∘ (lat.)×0.2∘ (lon.) spatial scale resolution. The geoelectric field dynamic mapping output gives both spatial and temporal variations of the magnitude and direction of fields. The GEDMap results show very rapid and strong variability of geoelectric field and the extremely localized peak enhancements. The magnitude of geoelectric fields over Mäntsälä at the time of the two GIC peaks were 279.7 mV/km and 336.9 mV/km. The comparison of the GIC measurements in Mäntsälä and our modeling results show very good agreement with a correlation coefficient higher than 0.8. It is found that the auroral electrojet geoelectric field has very rapid changes in both magnitude and orientation causing the GICs. It is also shown that the electrojet is not simply oriented in the east-west direction. It is possible that even higher time resolution base magnetometer data of 1 s will yield even more structure, so this will be our next effort.

Understanding Problem Forecasts of ISEST Campaign Flare-CME Events **Review**

David **Webb**, Nariaki Nitta

2017 Solar Physics 292(10) 142 **File**

https://link.springer.com/content/pdf/10.1007%2Fs11207-017-1166-4.pdf

The goal of the International Study of Earth-affecting Solar Transients (ISEST) project as part of the Variability of the Sun and Its Terrestrial Impact (VarSITI) program is to understand the origin, evolution, and propagation of solar transients through the space between the Sun and Earth, and to improve our prediction capability for space weather. A goal of ISEST Working Group 4 (Campaign Events) is to study a set of well-observed Sun-to-Earth events to develop an understanding of why some events are successfully forecast (textbook cases), whereas others become problem or failed forecasts. In this article we study six cases during the rise of Solar Cycle 24 that highlight forecasting problems. Likely source coronal mass ejections (CMEs) were identified in all six cases, but the related solar surface activity ranged from uncertain or weak to X-class flares. The geoeffects ranged from none to severe as in the two Sun–Earth events in 2015 that caused severe storms. These events were chosen to illustrate some key problems in understanding the chain from cause to geoeffect. **6 Jan. 2012, 7 – 9 Mar. 2012, 12 – 14 July 2012, 23 – 24 July 2012, 4 – 8 Oct. 2012, 15 – 17 Mar. 2013, 1 June 2013, 7 – 9 Jan. 2014, 10 – 13 Sep. 2014, 15 – 17 Mar. 2015, 21 – 24 June 2015**

Using STEREO-B as an L5 Space Weather Pathfinder Mission

D. F. **Webb**1 , D. A. Biesecker2 , N. Gopalswamy3 , O. C. St. Cyr3 , J. M. Davila3 , C. J. Eyles4 , B. J. Thompson3 , K. D. C. Simunac5 and J. C. Johnston6]

Space Research Today Volume 178, August **2010**, Pages 10-16

https://www.sciencedirect.com/science/article/pii/S1752929810000344

Studying geoeffective ICMEs between the Sun and Earth: Space weather implications of SMEI observations,

Webb, D.F., T.A. Howard, C.D. Fry, T.A. Kuchar, D.R. Mizuno, J.C. Johnston, and B.V. Jackson
Space Weather, 7, S05002, doi:10.1029/2008SW000409, 2009.

http://www.boulder.swri.edu/~howard/Papers/2009_Webb_SWx.pdf - **File**

Interplanetary coronal mass ejections (ICMEs) are the primary cause of severe space weather at Earth because they drive shocks and trigger geomagnetic storms that can damage spacecraft and ground-based systems. The Solar Mass Ejection Imager (SMEI) is a U. S. Air Force experiment with the ability to track ICMEs in white light from near the Sun to Earth and beyond, thus providing an extended observational range for forecasting storms. We summarize several studies of SMEI's detection and tracking capability, especially of the ICMEs associated with the intense (peak Dst _ _100 nT) geomagnetic storms that were the focus of the NASA Living With a Star Geostorm Coordinated Data Analysis Workshop. We describe the SMEI observations and analyses for the 18 intense storms observed from May 2003--2007 with adequate SMEI coverage and identified solar and interplanetary source regions. SMEI observed the associated ICMEs for 89% of these intense storms. For each event we extracted the time differences between these sets of times at 1 AU for shock arrival time, predicted ICME arrival time, onset of high-altitude aurora observed by SMEI, and storm onset. The mean intervals between successive pairs of these data were found to each be _4 hours. On average, SMEI first detected the geoeffective ICME about 1 day in advance, yielding a prediction lead time of _18 hours. Finally, the RMS values for the ICME-shock and storm-ICME time differences were determined, and provide at least a 1-hour improvement compared to similar observational and model-dependent studies.

Coronal mass ejections and space weather Review

D. F. **Webb** and N. Gopalswamy

in "Solar Influence on the Heliosphere and Earth's Environment: Recent Progress and Prospects", ed. N. Gopalswamy and A. Battacharyya, Quest Publications, Mumbai, p. 71, **2006. File**

http://cdaw.gsfc.nasa.gov/publications/ilws_goa2006/

Coronal mass ejections (CMEs) are a key feature of coronal and interplanetary (IP) dynamics. Major CMEs inject large amounts of mass and magnetic fields into the heliosphere and, when aimed Earthward, can cause major geomagnetic storms and drive IP shocks, a key source of solar energetic particles. Studies over this solar cycle using the excellent data sets from the SOHO, TRACE, Yohkoh, Wind, ACE and other spacecraft and ground-based instruments have improved our knowledge of the origins and early development of CMEs at the Sun and how they affect space weather at Earth. A new heliospheric experiment, the Solar Mass Ejection Imager, has completed 3 years in orbit and has obtained results on the propagation of CMEs through the inner heliosphere and their geoeffectiveness. We review key coronal properties of CMEs, their source regions, their manifestations in the solar wind, and their geoeffectiveness. Halo-like CMEs are of special interest for space weather because they suggest the launch of a geoeffective disturbance toward Earth. However, not all halo CMEs are equally geoeffective and this relationship varies over the solar cycle. Although CMEs are involved with the largest storms at all phases of the cycle, recurrent features such as interaction regions and high speed wind streams can also be geoeffective.

Spacecraft and Ground Anomalies Related to the October-November 2003 Solar Activity,

Webb, D. and J. Allen,

Space Weather, 2, S03008, doi:10.1029/2004SW000075 (**2004**)

Quantitative Prediction of High-Energy Electron Integral Flux at Geostationary Orbit Based on Deep Learning

Lihang **Wei** , Qiuzhen Zhong , Ruilin Lin , Jingjing Wang , Siqing Liu , Yong Cao

Space Weather Volume16, Issue7 July **2018** Pages 903-916

http://sci-hub.tw/10.1029/2018SW001829

The deep learning method of long short-term memory (LSTM) is applied to develop a model to predict the daily >2-MeV electron integral flux 1 day ahead at geostationary orbit. The inputs to the model include geomagnetic and solar wind parameters such as Kp, Ap, Dst, solar wind speed, magnetopause subsolar distance, and the value of >2-MeV electron integral flux itself over the previous five consecutive days. The model is trained on the data from the periods 1999–2007 and 2011–2016, and the efficiency of the model is tested on the 2008–2010 period. We experiment with different input combinations and find that when the model takes daily >2-MeV electron integral flux, daily averaged magnetopause subsolar distance, and daily summed Kp index as inputs, the prediction efficiencies for 2008, 2009, and 2010 are 0.833, 0.896, and 0.911, respectively. This value reaches 0.900 for 2008, when hourly >2-MeV electron integral flux, hourly magnetopause subsolar distance, and daily summed Kp index are taken as inputs, with training on the remaining data from 19 June 2003 to 13 April 2010. The prediction efficiencies of the persistence model and the 27-order autoregressive model for the same tested time period are 0.679 and 0.743, respectively. Therefore, the model developed based on the LSTM method can improve the prediction efficiency significantly for daily >2-MeV electron integral flux 1 day ahead at geostationary orbit.

LUCI onboard Lagrange, the next generation of EUV space weather monitoring

Matthew J. **West**1,2*, Christian Kintziger3, Margit Haberreiter4, Manfred Gyo4, David Berghmans1, Samuel Gissot1, Valeria Büchel4, Leon Golub5, Sergei Shestov1,6 and Jackie A. Davies

J. Space Weather Space Clim. **2020**, 10, 49

https://www.swsc-journal.org/articles/swsc/pdf/2020/01/swsc200056.pdf

https://doi.org/10.1051/swsc/2020052

Lagrange eUv Coronal Imager (LUCI) is a solar imager in the Extreme UltraViolet (EUV) that is being developed as part of the Lagrange mission, a mission designed to be positioned at the L5 Lagrangian point to monitor space weather from its source on the Sun, through the heliosphere, to the Earth. LUCI will use an off-axis two mirror design equipped with an EUV enhanced active pixel sensor. This type of detector has advantages that promise to be very beneficial for monitoring the source of space weather in the EUV. LUCI will also have a novel off-axis wide field-of-view, designed to observe the solar disk, the lower corona, and the extended solar atmosphere close to the Sun–Earth line. LUCI will provide solar coronal images at a 2–3 min cadence in a pass-band centred on 19.5. Observations made through this pass-band allow for the detection and monitoring of semi-static coronal structures such as coronal holes, prominences, and active regions; as well as transient phenomena such as solar flares, limb coronal mass ejections (CMEs), EUV waves, and coronal dimmings. The LUCI data will complement EUV solar observations provided by instruments located along the Sun–Earth line such as PROBA2-SWAP, SUVI-GOES and SDO-AIA, as well as provide unique observations to improve space weather forecasts. Together with a suite of other remote-sensing and in-situ instruments onboard Lagrange, LUCI will provide science quality operational observations for space weather monitoring.

Incorporation of Heliospheric Imagery into the CME Analysis Tool for improvement of CME Forecasting

S. J. **Wharton**, G. H. Millward, S. Bingham, E. M. Henley, S. Gonzi, D. R. Jackson
Space Weather Volume17, Issue8 Pages 1312-1328 **2019** **File**
sci-hub.se/10.1029/2019SW002166
Coronal Mass Ejections (CMEs) cause the largest geomagnetic disturbances at Earth which impact satellites, wired communication systems and power grids. The CME Analysis Tool (CAT) is used to determine a CME's initial longitude, latitude, angular width and radial speed from coronagraph images. These are the initial conditions for the Wang-Sheeley-Arge (WSA) Enlil solar wind model, along with the ambient solar wind properties derived from magnetograms. However, the coronagraph imagery is limited by field of view. We have incorporated heliospheric imagery (HI) from the Solar Terrestrial Relations Observatory (STEREO) into CAT to create the CME Analysis Tool with Heliospheric Imagery (CAT-HI). These HI images have a larger field of view, allowing tracking of CMEs to greater distances from the Sun. We have compared the performances of CAT and CAT-HI by examining the expected arrival times of CMEs at the L1 Lagrange point and found them to be consistent. However, CAT-HI is advantageous because it could be used to prune ensemble forecasts and issue routine updates for CME arrival time forecasts. Finally, we discuss CAT-HI in the context of an operational mission at the L4 or L5 Lagrange points.
Table 1. Initial parameters for CMEs analysed in this study. (2016-2017)
Table 2. Results of statistical test for acceleration/deceleration. For each CME,

Solar radio bursts and space weather

White, S.M.: **2007**,
Asian J. Phys. **16**, 189 – 207.
a non-CME type II burst that occurred on 16 July 2004.

Space Weather Studies in Australia

Wilkinson, Philip
Space Weather, Vol. 7, No. 6, S06002, **2009**
http://dx.doi.org/10.1029/2009SW000485
Space weather—the space-based phenomena that affect human and technological systems—can damage orbiting satellites and harm humans in space. But on a more regional level, space weather can induce currents on long conductors, such as pipelines and power lines. It can also disrupt radio communications between ground locations and aircraft. Most Northern Hemisphere countries monitor regional effects from adverse space weather in their hemisphere. Their collective research and calculations provide a comprehensive view of the phenomena that affect their region.

Automated detection of coronaL MAss ejecta origiNs for space weather AppliCations (ALMANAC)

Thomas **Williams**, Huw Morgan
Space Weather **2022**
https://arxiv.org/pdf/2211.04405.pdf
Alerts of potentially hazardous coronal mass ejections (CME) are based on the detection of rapid changes in remote observations of the solar atmosphere. This paper presents a method that detects and estimates the central coordinates of CME eruptions in Extreme Ultraviolet (EUV) data, with the dual aim of providing an early alert, and giving an initial estimate of the CME direction of propagation to a CME geometrical model. In particular, we plan to link the ALMANAC method to the CME detection and characterisation module of the Space Weather Empirical Ensemble Package (SWEEP), which is a fully automated modular software package for operational space weather capability currently being developed for the UK Meteorological Office. In this work, ALMANAC is applied to observations by the Atmospheric Imaging Assembly (AIA) aboard the Solar Dynamics Observatory (SDO). As well as presenting the method, a proof of concept test is made on a limited set of data associated with twenty halo CMEs recorded by the Coordinated Data Analysis Workshop (CDAW) catalogue near the activity maximum of solar cycle 24. SDO/AIA data for each event is processed at 6 minute cadence to identify the on-disk location and time of each

CME. The absolute mean deviance between the ALMANAC and CDAW source event coordinates are within 37.05 +- 29.71 minutes and 11.01 +- 10.39 degrees. These promising results give a solid foundation for future work, and will provide initial constraints to an automated CME alert and forecasting system. **2010-08-14, 2011-09-06, 2012-04-07, 2013-07-09, 2013 - 08 – 20, 2014-04-01**

Table 1. The results of CME source location obtained with ALMANAC for twenty example halo - CMEs identified from CDAW. 2010-2014

National Space Weather Program Releases Strategy for the New Decade

Williamson, Samuel P.; Babcock, Michael R.; Bonadonna, Michael F.

Space Weather, Vol. 8, No. 12, S12001, **2010**

http://dx.doi.org/10.1029/2010SW000637

The National Space Weather Program (NSWP; http://www.nswp.gov) is a U.S. federal government interagency program established by the Office of the Federal Coordinator for Meteorology (OFCM) in 1995 to coordinate, collaborate, and leverage capabilities across stakeholder agencies, including space weather researchers, service providers, users, policy makers, and funding agencies, to improve the performance of the space weather enterprise for the United States and its international partners. Two important documents released in recent months have established a framework and the vision, goals, and strategy to move the enterprise forward in the next decade. The U.S. federal agency members of the NSWP include the departments of Commerce, Defense, Energy, Interior, State, and Transportation, plus NASA, the National Science Foundation, and observers from the White House Office of Science and Technology Policy (OSTP) and the Office of Management and Budget (OMB). The OFCM is also working with the Department of Homeland Security's Federal Emergency Management Agency to formally join the program.

Spectral scaling technique to determine extreme Carrington-level geomagnetically induced currents effects

Lisa M. **Winter**, Jennifer Gannon, Rick Pernak, Stuart Huston, Richard Quinn, Edward Pope, Alexis Ruffenach, Pietro Bernardara, Nicholas Crocker

Space Weather Volume 15, Issue 5 May **2017** Pages 713–725

http://sci-hub.cc/10.1002/2016SW001586

Space weather events produce variations in the electric current in the Earth's magnetosphere and ionosphere. From these high-altitude atmospheric regions, resulting geomagnetically induced currents (GICs) can lead to fluctuations in ground currents that affect the electric power grid and potentially overload transformers during extreme storms. The most extreme geomagnetic storm on record, known as the 1859 Carrington event, was so intense that ground-based magnetometers were saturated at high magnetic latitudes. The most reliable, unsaturated observation is the hour resolution data from the Colaba Magnetic Observatory in India. However, higher-frequency components—fluctuations at second through minute time cadence—to the magnetic field can play a significant role in GIC-related effects. We present a new method for scaling higher-frequency observations to create a realistic Carrington-like event magnetic field model, using modern magnetometer observations. Using the magnetic field model and ground conductivity models, we produce an electric field model. This method can be applied to create similar magnetic and electric field models for studies of GIC effects on power grids.

Using the maximum X-ray flux ratio and X-ray background to predict solar flare class

L. M. **Winter**, K. Balasubramaniam

Space Weather Volume 13, Issue 5 May **2015** Pages 286–297

http://arxiv.org/pdf/1504.00294v1.pdf

We present the discovery of a relationship between the maximum ratio of the flare flux (namely, 0.5–4 Å to the 1–8 Å flux) and nonflare background (namely, the 1–8 Å background flux), which clearly separates flares into classes by peak flux level. We established this relationship based on an analysis of the Geostationary Operational Environmental Satellites X-ray observations of ~ 50,000 X, M, C, and flares derived from the NOAA/Space Weather Prediction Center flares catalog. Employing a combination of machine learning techniques (K-nearest neighbors and nearest centroid algorithms) we show a separation of the observed parameters for the different peak flaring energies. This analysis is validated by successfully predicting the flare classes for 100% of the X-class flares, 76% of the M-class flares, 80% of the C-class flares, and 81% of the B-class flares for solar cycle 24, based on the training of the parametric extracts for solar flares in cycles 22–23.

Estimate of Solar Maximum using the 1-8 ÅGeostationary Operational Environmental Satellites X-ray Measurements

L.M. **Winter** (AER), K. S. Balasubramaniam

ApJL, 793 L45 **2014**

http://arxiv.org/pdf/1409.2763v1.pdf

We present an alternate method of determining the progression of the solar cycle through an analysis of the solar X-ray background. Our results are based on the NOAA Geostationary Operational Environmental Satellites (GOES) X-ray data in the 1-8 \AAband from 1986 - present, covering solar cycles 22, 23, and 24. The X-ray background level tracks the progression of the solar cycle through its maximum and minimum. Using the X-ray data, we can therefore make estimates of the solar cycle progression and date of solar maximum. Based upon our analysis, we conclude that the Sun reached its hemisphere-averaged maximum in Solar Cycle 24 in late 2013. This is within six months of the NOAA prediction of a maximum in Spring 2013.

The variability of solar EUV: A multiscale comparison between sunspot number, 10.7 cm flux, LASP MgII index, and SOHO/SEM EUV flux

Peter **Wintoft**

Journal of Atmospheric and Solar-Terrestrial Physics, Volume 73, Issue 13, **2011**, 1708-1714

The sunspot number (SSN), 10.7 cm radio flux (F10.7), MgII index, and SOHO/SEM EUV flux have been studied, using wavelet analysis, in order to describe how the first three parameters are related to EUV on scales of days to years. The wavelet transform decomposes the time series into series which captures variability on different temporal scales. The three proxies show weak correlation on time scales of days, thus they are of limited use in space weather when the day-to-day variability is considered. However, the underlying modulation due to the solar rotation and the solar activity cycle is so strong that there is a big influence on the daily values. Both F10.7 and MgII show a more persistent increase in correlation with scale than SSN and should be the preferred proxies. When a linear regression model is used for SEM/EUV the RMS error is about 26% lower, for the analysed period (1996–2010), for MgII compared to F10.7. However, when only the long term is considered (scale 1.4 yr) the RMS error is 20% larger when MgII is used compared to F10.7. This is caused by an offset between MgII and SEM that appears around the cycle 23 maximum. This offset is not seen between F10.7 and SEM. For space weather purposes, although none of the studied proxies works on a daily basis, the MgII index performs the best, but for the longer time scales F10.7 is the most suitable.

Verification of real-time WSA-ENLIL+Cone simulations of CME arrival-time at the CCMC from 2010-2016

A. M. **Wold**, M. L. Mays, A. Taktakishvili, L. K. Jian, D. Odstrcil, P. MacNeice

Journal of Space Weather and Space Climate 8, A17 **2018**

https://arxiv.org/pdf/1801.07818.pdf

https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc170034.pdf

The Wang-Sheeley-Arge (WSA)-ENLIL+Cone model is used extensively in space weather operations world-wide to model CME propagation. As such, it is important to assess its performance. We present validation results of the WSA-ENLIL+Cone model installed at the Community Coordinated Modeling Center (CCMC) and executed in real-time by the CCMC space weather team. CCMC uses the WSA-ENLIL+Cone model to predict CME arrivals at NASA missions throughout the inner heliosphere. In this work we compare model predicted CME arrival-times to in-situ ICME leading edge measurements at STEREO-A, STEREO-B, and Earth (Wind and ACE) for simulations completed between March 2010-December 2016 (over 1,800 CMEs). We report hit, miss, false alarm, and correct rejection statistics for all three locations. For all predicted CME arrivals, the hit rate is 0.5, and the false alarm rate is 0.1. For the 273 events where the CME was predicted to arrive at Earth, STEREO-A, or STEREO-B, and was actually observed (hit event), the mean absolute arrival-time prediction error was 10.4 +/- 0.9 hours, with a tendency to early prediction error of -4.0 hours. We show the dependence of the arrival-time error on CME input parameters. We also explore the impact of the multi-spacecraft observations used to initialize the model CME inputs by comparing model verification results before and after the STEREO-B communication loss (since September 2014) and STEREO-A sidelobe operations (August 2014-December 2015). There is an increase of 1.7 hours in the CME arrival time error during single, or limited two-viewpoint periods, compared to the three-spacecraft viewpoint period. This trend would apply to a future space weather mission at L5 or L4 as another coronagraph viewpoint to reduce CME arrival time errors compared to a single L1 viewpoint.

Turbulence-Driven Coronal Heating and Improvements to Empirical Forecasting of the Solar Wind

Lauren N. **Woolsey**, Steven R. Cranmer

ApJ, **2014**

http://arxiv.org/pdf/1404.5998v1.pdf

Forecasting models of the solar wind often rely on simple parameterizations of the magnetic field that ignore the effects of the full magnetic field geometry. In this paper, we present the results of two solar wind prediction models that consider the full magnetic field profile and include the effects of Alfv\'en waves on coronal heating and wind acceleration. The one-dimensional MHD code ZEPHYR self-consistently finds solar wind solutions without the

need for empirical heating functions. Another 1D code, introduced in this paper (The Efficient Modified-Parker-Equation-Solving Tool, TEMPEST), can act as a smaller, stand-alone code for use in forecasting pipelines. TEMPEST is written in Python and will become a publicly available library of functions that is easy to adapt and expand. We discuss important relations between the magnetic field profile and properties of the solar wind that can be used to independently validate prediction models. ZEPHYR provides the foundation and calibration for TEMPEST, and ultimately we will use these models to predict observations and explain space weather created by the bulk solar wind. We are able to reproduce with both models the general anticorrelation seen in comparisons of observed wind speed at 1 AU and the flux tube expansion factor. There is significantly less spread than comparing the results of the two models than between ZEPHYR and a traditional flux tube expansion relation. We suggest that the new code, TEMPEST, will become a valuable tool in the forecasting of space weather.

International cooperation: A brief history We've experienced **Review**

Wu Ji1,2*, Bai Qingjiang1 and Xu Yongjian1
J. Space Weather Space Clim. **2021**, 11, 27
https://doi.org/10.1051/swsc/2021008
https://www.swsc-journal.org/articles/swsc/pdf/2021/01/swsc200099.pdf
The solar-terrestrial space is of considerable significance for human activities. Since the first artificial satellite Sputnik 1 was launched in 1957, more knowledge about the dynamic conditions of the space environment has been acquired. With growing dependence on modern technology – both in space and on the ground, the vulnerability of the modern society and its infrastructure to space weather has increased dramatically. To better understand, forecast and reduce the adverse effects of space weather, science programs on space weather always prioritize the measurement or acquisition of the data from different locations of the geo-space, such as in magnetopause, polar cusps, and the magnetic tail. For the ground observations, it is necessary to locate the instruments in different longitudes and latitudes. For a single country, it is impossible to cover all these observation points. Therefore, international cooperation is very much needed. The paper reviews some of the international space weather observation programs we have experienced at the system design level. It may provide lessons learned for the community that may enable such kind of cooperative programs in the future.

Short-Term Lightning Response to Ground Level Enhancements

Qiong **Wu**1,2, Hui Li1,3* and Chi Wang1,4
Frontier Phys., 8:348 **2020** |
https://doi.org/10.3389/fphy.2020.00348
https://www.frontiersin.org/articles/10.3389/fphy.2020.00348/full?utm_source=F-AAE&utm_medium=EMLF&utm_campaign=MRK_1427535_64_Physic_20200908_arts_A
https://sci-hub.st/10.3389/fphy.2020.00348
Cosmic rays (CRs) are considered the primary energetic particle source of atmospheric ionization on Earth. Under the modulation of severe solar eruption events, CR variations are further speculated to impact the Earth's lightning activities. Previous researches show that CR intensity and lightning incidence are positively correlated on the time scale of several days to decades. However, to our knowledge, the global lightning response to short-term CR variation has not been studied in the literature. Ground level enhancements (GLEs) provide the opportunity to study such a possible link. As a small fraction of solar energetic particle events that could reach the energy level of several GeVs, GLEs can thus generate atmospheric cascades that could be recorded by ground-based neutron monitors. Furthermore, as GLEs generally take place within several 10 min to an hour, the lightning variations caused by potential meteorological factors could be maximally diminished in such a short time. During the operational period of the World Wide Lightning Location Network (Aug 2004 to now), three typical GLEs with the intensity >15% are analyzed from the International GLE Database, namely #69 (**Jan 20, 2005**), #70 (**Dec 13, 2006**), and #71 (**May 17, 2012**). For each GLE event, the global lightning incidence presents a positive response to GLE (i.e., a significant enhancement within 20 min right after the GLE onset). Meanwhile, the relative amplitude of lightning response seems to be in direct proportion to GLE intensity (i.e., the more intensive the GLE is, the more obvious the increase in the lightning incidence is), which is further verified to be statistically significant by Monte Carlo test. By comparing lightning responses in different latitudinal zones, we find that more intensive lightning responses to GLEs seem to be at higher latitudes.

Features and Source Current of Long-period Induced Geoelectric Field during Magnetic Storms:A Case Study

S.Y. **Wu** , S. Yao , X.D. Feng , W.B. Wei , Y.T. Yin , L.T. Zhang , H. Dong , G.W. Wang , J.J. Liu, Y.Q. Yu , D. Wei
Space Weather **2020**
sci-hub.se/10.1029/2019SW002298

We present a case study on the long-period (> 105 s) induced geoelectric field disturbance during magnetic storms. A set of continuous 33-day measurements of the geoelectric field, geomagnetic field, geomagnetic indices, and interplanetary magnetic field are analyzed. In the studied 33 days, two magnetic storms occured after 10 geomagnetic quiet days. To exclude the effects from the different underground electrical structures, geomagnetic and geoelectric field measurements from the same ground observatory enrolled in Chinese Meridian Project are studied. Besides, Space Weather Modelling Framework is adopted to calculate the global geomagnetic field disturbances and the contribution from different current systems. The wavelet power spectra analysis reveals that the long-period (LP) geoelectric field disturbance appears only during magnetic storms. Especially, stronger magnetic storm generates weaker geoelectric disturbances at the same observatory. The opposite-direction eastward geomagnetic field disturbance, which is generated mainly by the field-aligned current at different magnetic local time, significantly changes the magnitude and direction of the induced geoelectric field via the underground impedance tensor. Therefore, both the effects caused by ring current and field-aligned current should be considered in analyzing the ground induced geoelectric field. Excluding the effect from the geospace current source, the more accurate electrical conductivity in the upper mantle would be obtained in future. **21 Oct to 22 Nov, 2012**

The SPORT Mission: A New Observatory of Interplanetary CMEs from Solar Polar Orbit

Ji **Wu**, Weiying Sun, Jianhua Zheng, Cheng Zhang, Chi Wang ...
Space Research Today Volume 178, August **2010**, Pages 2-9
https://www.sciencedirect.com/science/article/pii/S1752929810000332

Periods of high intensity solar proton flux.

Xapsos MA, Stauffer CA, Jordan TM, Adams JH, Dietrich WF
(**2012**) IEEE Trans Nucl Sci 59:1054.
sci-hub.si/10.1109/TNS.2012.2196447
Analysis is presented for times during a space mission that specified solar proton flux levels are exceeded. This includes both total time and continuous time periods during missions. Results for the solar maximum and solar minimum phases of the solar cycle are presented and compared for a broad range of proton energies and shielding levels. This type of approach is more amenable to reliability analysis for spacecraft systems and instrumentation than standard statistical models.

The Swarm satellite loss of GPS signal and its relation to ionospheric plasma irregularities

Chao **Xiong**, Claudia Stolle, Hermann Lühr
Space Weather Volume 14, Issue 8 August **2016** Pages 563–577
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2016SW001439
In this study we investigated conditions for loss of GPS signals observed by the Swarm satellites during a 2 year period, from December 2013 to November 2015. Our result shows that theSwarm satellites encountered most of the total loss of GPS signal at the ionization anomaly crests, between ±5° and ±20° magnetic latitude, forming two bands along the magnetic equator, and these low-latitude events mainly appear around postsunset hours from 19:00 to 22:00 local time. By further checking the in situ electron density measurements of Swarm, we found that practically, all the total loss of GPS signal events at low latitudes are related to equatorial plasma irregularities (EPIs) that show absolute density depletions larger than 10 × 1011 m−3; then, the Swarm satellites encountered for up to 95% loss of GPS signal for at least one channel and up to 45% tracked less than four GPS satellites (making precise orbit determination impossible). For those EPIs with density depletions less than 10 × 1011 m−3, the chance of tracked GPS signals less than four reduces to only 1.0%. Swarm also observed total loss of all GPS signal at high latitudes, mainly around local noon, and these events are related to large spatial density gradients due to polar patches or increased geomagnetic/auroral activities. We further found that the loss of GPS signals were less frequent after appropriate settings of theSwarm GPS receivers had been updated. However, the more recent period of the mission, e.g., after the GPS receiver settings have been updated, also coincides with less severe electron density depletions due to the declining solar cycle, making GPS loss events less likely. We conclude that both lower electron density gradients and appropriate GPS receiver settings reduce the probability for Swarm satellites loss of GPS signals.

A statistic study of ionospheric solar flare activity indicator

Xiong, B., Wan, W., Ning, B., Ding, F., Hu, L., Yu, Y.:
2014, *Space Weather*. Volume 12, Issue 1, pp. 29-40
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2013SW001000
According to the Chapman ionization theory, an ionospheric solar flare activity indicator (ISFAI) is given by the solar zenith angle and the variation rate of ionospheric vertical total electron content, which is measured from a global network of dual-frequency GPS receivers. The ISFAI is utilized to statistically analyze the ionospheric responses to **1439 M-class and 126 X-class solar flares during solar cycle 23** (1996–2008). The statistical results show that the occurrence of ISFAI peak increases obviously at 3.2 total electron content unit (TECU)/h (1

TECU = 1016 el m−2) and reaches the maximum at 10 TECU/h during M-class flares and 10 TECU/h and 40 TECU/h for X-class flares. ISFAI is closely correlated with the 26–34 nm extreme ultraviolet flux but poorly related to the 0.1–0.8 nm X-ray flux. The central meridian distance (CMD) of flare location is an important reason for depressing relationship between ISFAI and X-ray Flux. Through the CMD effect modification, the ISFAI has a significant dependence on the X-ray flux with a correlation coefficient of 0.76. The ISFAI sensitivity enables to detect the extreme X-class flares, as well as the variations of one order of magnitude or even smaller (such as for C-class flares). Meanwhile, ISFAI is helpful to the calibration of the X-ray flux at 0.1–0.8 nm observed by GOES during some flares. In addition, the statistical results demonstrate that ISFAI can detect 80% of all M-class flares and 92% for all X-class ones during 1996–2008. **22 November 1998 , 24 April 2001**

Importance of Shock Compression in Enhancing ICME's Geoeffectiveness

Mengjiao **Xu**1, Chenglong Shen1,2, Yuming Wang1,2,3, Bingxian Luo4,5, and Yutian Chi1
2019 ApJL 884 L30
https://doi.org/10.3847/2041-8213/ab4717

Shock embedded interplanetary coronal mass ejections (ICMEs) are of great interest in the solar and heliosphere physics community due to their high potential to cause intense geomagnetic storms. In this work, **18 moderate to intense geomagnetic storms** caused by shock-ICME complex structures are analyzed in order to show the importance of shock compression in enhancing ICMEs' geoeffectiveness. Based on the characteristics of the shocks inside ICMEs, including the shock velocity, shock normal direction, and the density compression ratio, we recover the shocked part in the ICME to the uncompressed state by using a recovery model developed by Wang et al. according to the Rankine–Hugoniot relationship. Comparing the observational data and the recovered parameters, we find that the maximum southward magnetic field in the ICME is doubled and the dawn–dusk electric field is increased 2.2 times due to the shock compression. Then, the parameters of the observed and recovered solar wind and magnetic field are, respectively, introduced into various Dst prediction models. The prediction results show that, on average, the shock compression can enhance the intensity of the geomagnetic storm by a factor of 1.4. Without shock compression, the geoeffectiveness of these ICMEs would be markedly reduced. Moreover, there is a significant correlation between the shock density compression ratio and the shock's capacity of strengthening geomagnetic storms. The larger the shock density compression ratio is, the more obvious Dst index decrease is caused.

Space Weather Effects on Transportation Systems: A Review of Current Understanding and Future Outlook **Review**

Dabin **Xue**, Lingxiao Wu, Tianhe Xu, Cheng-Lung Wu, Zhipeng Wang, Zhengbing He
Space Weather Volume22, Issue12 December **2024** e2024SW004055
https://doi.org/10.1029/2024SW004055
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2024SW004055

Space weather events, including solar flares, coronal mass ejections, and geomagnetic storms, have significant effects on various transportation systems. This review provides a comprehensive examination of the current understanding and future outlook of space weather effects on air, maritime, railway, and ground transportation. It explores the mechanisms through which space weather causes communication blackouts, satellite navigation failure, elevated cosmic radiation, and geomagnetically induced currents, leading to disruptions in transportation operations. Historical events are analyzed to underscore the diversity and severity of these impacts. Additionally, this review discusses the anticipated challenges posed by the upcoming solar maximum of Solar Cycle 25 and highlights the need for improved forecasting, mitigation strategies, and resilient infrastructure to safeguard transportation systems against space weather threats. By integrating findings from recent studies and historical data, this review aims to enhance the preparedness and response strategies of the transportation sector in the face of evolving space weather risks.

Optimizing Polar Air Traffic: Strategies for Mitigating the Effects of Space Weather-Induced Communication Failures Poleward of 82°N

Dabin **Xue**, Zhizhao Liu, Donghe Zhang, Cheng-Lung Wu, Jian Yang
Space Wather Volume22, Issue12 December **2024** e2024SW004136
https://doi.org/10.1029/2024SW004136
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2024SW004136

Aviation communication is significant for the safe, efficient, and orderly operation of air traffic. The aviation industry relies on a sophisticated network to maintain air-ground communications. However, space weather events can disrupt the ionosphere conditions and damage satellites, leading to High-Frequency (HF) communication blackouts and satellite communication failures. These disruptions can jeopardize flight safety, especially for flights over polar regions. In response, strategies such as cancellations, rescheduling, or rerouting to lower latitudes may be necessary, despite the low flight efficiency and substantial financial losses. With the background of the anticipated solar maximum in 2025 and a growing number of polar flights, it is indispensable to have a comprehensive understanding of the space weather effects on aviation communication and develop constructive strategies from an Air Traffic Management (ATM) perspective. Hence, we simulate scenarios with different durations of communication failures and assess the corresponding economic losses. Based on the data derived from historical polar flights in 2019, there are daily 18 polar flights with trajectories crossing the north polar region higher than 82°N. Simulation results show that the economic losses associated with these polar flights can range from €0.03 million to €1.32 million, depending on both the duration of communication failures and the adopted air traffic management strategies. We believe that this study can shed light on the effects of space weather-induced communication failures on polar flight operations and provide guidance for mitigating these effects in the aviation industry.

Forward-Looking Study of Solar Maximum Impact in 2025: Effects of Satellite Navigation Failure on Aviation Network Operation in the Greater Bay Area, China

Dabin **Xue**, Jian Yang, Zhizhao Liu, Wei Cong

Space Weather Volume21, Issue12 December **2023** e2023SW003678
https://doi.org/10.1029/2023SW003678
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Satellite navigation based on the Global Navigation Satellite System can provide aircraft with more precise guidance and increase flight efficiency. However, severe space weather events can cause satellite navigation failure due to the dramatic increase in total electron content and irregularities in the ionosphere. Consequently, ground navigation has to be used to replace satellite navigation, increasing aircraft separation standards and reducing airspace capacity. As a result, numerous flights may be delayed or even canceled, incurring significant financial losses. The occurrence peak of space weather events generally coincides with the 11-year-cycle solar maximum, and 2025 is expected to be the upcoming solar maximum. The Greater Bay Area (GBA), located in the equatorial ionization anomaly region of China, is particularly vulnerable to space weather impacts. To explore the effects of satellite navigation failure on flight operation, we conduct this looking-forward study and propose solution methods from the standpoint of Air Traffic Management, by simulating satellite navigation failure scenarios. Based on the projected flight volume in 2025 related to the GBA airports, simulation results show that the economic costs can be tens of millions of Euros, which is dependent on the duration of satellite navigation failure and the time interval of ground navigation-based landing. We believe that this study can be a benchmark for evaluating the potential economic effects of forthcoming space weather on flight operations.

Examining the Economic Costs of the 2003 Halloween Storm Effects on the North Hemisphere Aviation Using Flight Data in 2019

Dabin **Xue**, Jian Yang, Zhizhao Liu, Shiwei Yu

Space Weather Volume21, Issue3 e2022SW003381 **2023**
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https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022SW003381

Space weather can impede normal aviation operations through communication blackouts, GNSS-based navigation and surveillance failures, and elevated cosmic radiation, consequently resulting in necessary flight plan adjustments and considerable economic costs. Although space weather effects have been heavily emphasized, the literature on the economic effects on aviation is limited. In this study, we estimate the economic impacts from the perspective of air traffic management, assuming an extremely strong space weather event like the 2003 Halloween solar storm would occur in 2019 with a booming air transport industry in recent years. We find that (a) as the high-frequency communication blackouts may lead to polar flight rerouting and cancellations, possible daily economic costs could range from €0.21 million to €2.20 million per day; (b) during the satellite navigation failure period in the continental United States, as aircraft utilizes ground navigation aids as a backup, the increased flying time and disrupted descent approach operations may lead to additional cost of €2.43 million; (c) a surveillance failure can reduce airspace capacity and increase the workload of air traffic controllers, resulting in fatigue and perhaps risking flight safety; (d) to prevent massive cosmic radiation exposure, the economic costs of flight cancellations can be from €2.77 million to €48.97 million, depending on the cosmic radiation dose limits for a given plan. Our study indicates that severe space weather events may briefly disrupt normal aviation operations and cause substantial economic losses if future aviation equipment and technology are fragile to its effects. **28–31 October 2003**

An optimized solution to long-distance flight routes under extreme cosmic radiation

Dabin **Xue**, Jian Yang, Zhizhao Liu, Bing Wang

Space Weather e2022SW003264 Volume20, Issue12 **2022**
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https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022SW003264

During extraordinary space weather, cosmic radiation can be significant enough to pose a threat to aircrew health. Traditional methods of reducing massive cosmic radiation exposure include flight cancellation, lowering flying altitudes, and flight rerouting. However, flight cancellation can result in additional financial expenditures, while

lowering flight altitudes and rerouting can consequently cause more fuel consumption or even violation of airspace rights. As a result, we use a multi-objective optimization model to assign optimal flight altitude and speed to reduce the overall weighted sum of cosmic radiation and fuel consumption. The simulation scenario is based on a space weather event with dramatically increased cosmic radiation that occurs during a routine international flight from Tokyo to London. Our results show that the proposed model can reduce fuel consumption while satisfying cosmic radiation limits recommended by the Council of the European Union if the forecasts of cosmic radiation are sufficiently accurate. In addition, a Pareto frontier is provided as a tactical air traffic management guideline. Our study provides insight into future policymaking for air transportation during harsh space weather conditions.

Cost estimation for alternative aviation plans against potential radiation exposure associated with solar proton events for the airline industry

Yosuke A. **Yamashiki**, Moe Fujita, Tatsuhiko Sato, Hiroyuki Maehara, Yuta Notsu, Kazunari Shibata

Evolutionary and Institutional Economics Review **2020**

https://arxiv.org/ftp/arxiv/papers/2004/2004.10869.pdf

We present a systematic approach to effectively evaluate potential risk cost caused by exposure to solar proton events (SPEs) from solar flares for the airline industry. We also evaluate associated health risks from radiation, to provide relevant alternative ways to minimize economic loss and opportunity. The estimated radiation dose induced by each SPE for the passengers of each flight is calculated using ExoKyoto and PHITS. We determine a few scenarios for the estimated dose limit at 1 and 20mSv, corresponding to the effective dose limit for the general public and occupational exposure, respectively, as well as a higher dose induced an extreme superflare. We set a hypothetical airline shutdown scenario at 1mSv for a single flight per passenger, due to legal restrictions under the potential radiation dose. In such a scenario, we calculate the potential loss in direct and opportunity cost under the cancelation of the flight. At the same time, we considered that, even under such a scenario, if the airplane flies at a slightly lower altitude (from 12 to 9.5km: atmospheric depth from 234 to 365g/cm2), the total loss becomes much smaller than flight cancelation, and the estimated total dose goes down from 1.2 to 0.45mSv, which is below the effective dose limit for the general public. In case of flying at an even lower altitude (7km: atmospheric depth 484g/cm2), the estimated total dose becomes much smaller, 0.12 mSv. If we assume the increase of fuel cost is proportional to the increase in atmospheric depth, the increase in cost becomes 1.56 and 2.07 for the case of flying at 9.5 km and at 7 km, respectively. Lower altitude flights provide more safety for the potential risk of radiation doses induced by severe SPEs. At the same time, since there is total loss caused by flight cancelation, we propose that considering lower flight altitude is the best protection against solar flares.

The 6 September 2017 X-Class Solar Flares and Their Impacts on the Ionosphere, GNSS, and HF Radio Wave Propagation

Y. **Yasyukevich** , E. Astafyeva , A. Padokhin, V. Ivanova, S. Syrovatskii, A. Podlesnyi

Space Weather Volume16, Issue8 August **2018** Pages 1013-1027

https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2018SW001932

http://sci-hub.tw/10.1029/2018SW001932

On 6 September 2017, the Sun emitted two significant solar flares (SFs). The first SF, classified X2.2, peaked at 09:10 UT. The second one, X9.3, which is the most intensive SF in the current solar cycle, peaked at 12:02 UT and was accompanied by solar radio emission. In this work, we study ionospheric response to the two X-class SFs and their impact on the Global Navigation Satellite Systems and high-frequency (HF) propagation. In the ionospheric absolute vertical total electron content (TEC), the X2.2 SF caused an overall increase of 2–4 TECU on the dayside. The X9.3 SF produced a sudden increase of ~8–10 TECU at midlatitudes and of ~15–16 TECU enhancement at low latitudes. These vertical TEC enhancements lasted longer than the duration of the EUV emission. In TEC variations within 2–20 min range, the two SFs provoked sudden increases of ~0.2 TECU and 1.3 TECU. Variations in TEC from geostationary and GPS/GLONASS satellites show similar results with TEC derivative of ~1.3–1.7 TECU/min for X9.3 and 0.18–0.24 TECU/min for X2.2 in the subsolar region. Further, analysis of the impact of the two SFs on the Global Navigation Satellite Systems-based navigation showed that the SF did not cause losses-of-lock in the GPS, GLONASS, or Galileo systems, while the positioning error increased by ~3 times in GPS precise point positioning solution. The two X-class SFs had an impact on HF radio wave propagation causing blackouts at <30 MHz in the subsolar region and <15 MHz in the postmidday sector.

Solar radio proxies for improved satellite orbit prediction

Philippe **Yaya**, Louis Hecker, Thierry Dudok de Wit, Clémence Le Fèvre and Sean Bruinsma

J. Space Weather Space Clim. **2017**, 7, A35

https://www.swsc-journal.org/articles/swsc/pdf/2017/01/swsc170049.pdf

Satellite operators routinely forecast orbits up to 30 days into the future. This requires forecasts of the drivers to these orbit prediction models such as the solar Extreme-UV (EUV) flux and geomagnetic activity. Most density models use the 10.7 cm radio flux (F10.7 index) as a proxy for solar EUV. However, daily measurements at other centimetric wavelengths have also been performed by the Nobeyama Radio Observatory (Japan) since the 1950's, thereby offering prospects for improving orbit modeling. Here we present a pre-operational service at the Collecte Localisation Satellites company that collects these different observations in one single homogeneous dataset and provides a 30 days forecast on a daily basis. Interpolation and preprocessing algorithms were developed to fill in missing data and remove anomalous values. We compared various empirical time series prediction techniques and selected a multi-wavelength non-recursive analogue neural network. The prediction of the 30 cm flux, and to a lesser extent that of the 10.7 cm flux, performs better than NOAA's present prediction of the 10.7 cm flux, especially during periods of high solar activity. In addition, we find that the DTM-2013 density model (Drag Temperature Model) performs better with (past and predicted) values of the 30 cm radio flux than with the 10.7 flux.

Superposed epoch analysis of the energetic electron flux variations during CIRs measured by BD-IES

Zefan **Yin**, Hong Zou, Yuguang Ye, Qiugang Zong, Yongfu Wang
Space Weather **2019**
sci-hub.se/10.1029/2019SW002296
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019SW002296
The flux variations of energetic electrons is one of the most important topics to understand dynamic processes in the space environment and the forecast for high-energy electron burst. BD-IES, an imaging energetic electron spectrometer onboard a Chinese navigation satellite at an inclined geosynchronous orbit (IGSO), can provide 50-600keV electron flux data, which is used to investigate electron flux variations at GEO orbit during Co-rotating Interaction Region events (CIRs). The superposed epoch analysis is applied to study the electron flux variations in different energy channels of BD-IES during CIRs and the results support previous works. It reveals that electron fluxes in different channels all have a dropout before or at CIR interface and then the recovery of electrons with low energy reaches maximum earlier than that of electrons with high energy, with longer time differences for larger energy gap, which is consistent of two major mechanisms for energizing particles: *inward radial diffusion and local acceleration*. In addition, we investigate the relationship between electron flux enhancement in each energy channel and magnetic local time (MLT) and the extent of enhancement for electron flux peak value compared with average value before interface. These results can contribute to our understanding of electron flux variations at GEO during CIRs, and thus lay foundations for forecast research on high-energy electron enhancement during CIRs.
Table 3. List of all CIR events used in this study (2016-2017)

Chapter 22 - The Effect of Solar Radio Bursts on GNSS Signals **Review**

Xinan **Yue**∗WeixingWan∗LimeiYan∗WenjieSun∗LianhuanHu∗William S.Schreiner†
In: Extreme Events in Geospace Origins, Predictability, and Consequences **2018**, Pages 541-554
http://sci-hub.ru/10.1016/B978-0-12-812700-1.00022-4
A solar radio burst (SRB) is the intense solar radio emission related to a solar flare and one of the extreme space weather events. If an SRB occurs with the enhancement in L band radio flux, it could influence the Global Navigation Satellite System (GNSS) signals through direct radio wave interferences. An SRB could result in reduction of signal-to-noise ratio (SNR) and instantaneous or long-period loss of lock (LOL) on GNSS signals. Therefore decreasing the observation quality, which subsequently will influence all the applications based on these observations such as radio occultation technique and precise GNSS positioning. An SRB will mainly affect stations located in the sunlit hemisphere during radio flux enhancement, while the strength of the influence depends on the solar incidence angle, the antenna pattern, the tracking algorithm, and some other factors. The threshold value of SRB flux value that could result in a significant effect on GNSS signals is believed to be between 1000–10,000 solar flux units (SFU; 1 SFU = 10^{-22} W m^{-2} Hz^{-1}) in L band. Significant SRBs can occur at solar minimum and maximum. During 2003–12, eight SRB events occurred that have shown degrading effects on GNSS signals in the literature, which is approximately 8.8 events per solar cycle. Although the occurrence ratio is not significantly high, we should pay sufficient attention to its side effects on modern society. **December 6, 2006**

The effect of solar radio bursts on the GNSS radio occultation signals.

Yue X, Schreiner WS, Kuo YH, Zhao B, Wan W, Ren Z, Liu L, Wei Y, Lei J, Solomon S, Rocken C.
2013. J Geophys Res Space Phys 118: 5906–5918.
http://dx.doi.org/10.1002/ jgra.50525
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/jgra.50525
Solar radio burst (SRB) is the radio wave emission after a solar flare, covering a broad frequency range, originated from the Sun's atmosphere. During the SRB occurrence, some specific frequency radio wave could interfere with the Global Navigation Satellite System (GNSS) signals and therefore disturb the received signals. In this study, the low

Earth orbit- (LEO-) based high-resolution GNSS radio occultation (RO) signals from multiple satellites (COSMIC, CHAMP, GRACE, SAC-C, Metop-A, and TerraSAR-X) processed in University Corporation for Atmospheric Research (UCAR) were first used to evaluate the effect of SRB on the RO technique. The radio solar telescope network (RSTN) observed radio flux was used to represent SRB occurrence. An extreme case during **6 December 2006** and statistical analysis during April 2006 to September 2012 were studied. The LEO RO signals show frequent loss of lock (LOL), simultaneous decrease on L1 and L2 signal-to-noise ratio (SNR) globally during daytime, small-scale perturbations of SNR, and decreased successful retrieval percentage (SRP) for both ionospheric and atmospheric occultations during SRB occurrence. A potential harmonic band interference was identified. Either decreased data volume or data quality will influence weather prediction, climate study, and space weather monitoring by using RO data during SRB time. Statistically, the SRP of ionospheric and atmospheric occultation retrieval shows ~4% and ~13% decrease, respectively, while the SNR of L1 and L2 show ~5.7% and ~11.7% decrease, respectively. A threshold value of ~1807 SFU of 1415 MHz frequency, which can result in observable GNSS SNR decrease, was derived based on our statistical analysis.

Coronal Hole Analysis and Prediction using Computer Vision and LSTM Neural Network

Juyoung **Yun**

2023

https://arxiv.org/pdf/2301.06732.pdf

As humanity has begun to explore space, the significance of space weather has become apparent. It has been established that coronal holes, a type of space weather phenomenon, can impact the operation of aircraft and satellites. The coronal hole is an area on the sun characterized by open magnetic field lines and relatively low temperatures, which result in the emission of the solar wind at higher than average rates. In this study, To prepare for the impact of coronal holes on the Earth, we use computer vision to detect the coronal hole region and calculate its size based on images from the Solar Dynamics Observatory (SDO). We then implement deep learning techniques, specifically the Long Short-Term Memory (LSTM) method, to analyze trends in the coronal hole area data and predict its size for different sun regions over 7 days. By analyzing time series data on the coronal hole area, this study aims to identify patterns and trends in coronal hole behavior and understand how they may impact space weather events. This research represents an important step towards improving our ability to predict and prepare for space weather events that can affect Earth and technological systems. 23-26 Dec 2022

What Is the Radiation Impact of Extreme Solar Energetic Particle Events on Mars?

Jian **Zhang**, Jingnan Guo, Mikhail I. Dobynde

Space Weather   e2023SW003490   Volume21, Issue6   **2023**

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2023SW003490

Solar Energetic Particles (SEP) are one of the major sources of the Martian radiation environment. It is important to understand the SEP-induced Martian radiation environment for future human habitats on Mars. Due to the lack of a global intrinsic magnetic field, Solar Energetic Particles (SEPs) can directly propagate through and interact with its atmosphere before reaching the surface and subsurface of Mars. Mars has many high mountains and low-altitude craters where the atmospheric thickness can be more than 10 times different than one another. The SEP-induced surface radiation level may therefore be very different from one location to another. We thus consider the influence of the atmospheric depths on the Martian radiation levels including the absorbed dose, dose equivalent, and (human-)body effective dose induced by SEPs at varying heights above and below the Martian surface. The state-of-the-art Atmospheric Radiation Interaction Simulator based on GEometry And Tracking Monte-Carlo method has been employed for simulating particle interactions with the Martian atmosphere and terrain. We find that even the thinnest Martian atmosphere reduces radiation dose from that in deep space by at least 65%, and the shielding effect increases for denser atmosphere. Furthermore, we present a method to quickly forecast the SEP-induced radiation in different regions of Mars with different surface pressures.

Earth-affecting Solar Transients: A Review of Progresses in Solar Cycle 24

Jie **Zhang**, Manuela Temmer, Nat Gopalswamy, Olga Malandraki, Nariaki V. Nitta, Spiros Patsourakos, Fang Shen, Bojan Vršnak, Yuming Wang, David Webb, Mihir I. Desai, Karin Dissauer, Nina Dresing, Mateja Dumbović, Xueshang Feng, Stephan G. Heinemann, Monica Laurenza, Noé Lugaz, Bin Zhuang

https://arxiv.org/ftp/arxiv/papers/2012/2012.06116.pdf   **File 2021**

2020   https://arxiv.org/abs/2012.06116

https://arxiv.org/ftp/arxiv/papers/2012/2012.06116.pdf

This review article summarizes the advancement in the studies of Earth-affecting solar transients in the last decade that encompasses most of solar cycle 24. The Sun Earth is an integrated physical system in which the space environment of the Earth sustains continuous influence from mass, magnetic field and radiation energy output of the Sun in varying time scales from minutes to millennium. This article addresses short time scale events, from minutes to days that directly cause transient disturbances in the Earth space environment and generate intense adverse effects on advanced technological systems of human society. Such transient events largely fall into the following four types: (1) solar flares, (2) coronal mass ejections (CMEs) including their interplanetary counterparts ICMEs, (3) solar energetic particle (SEP) events, and (4) stream interaction regions (SIRs) including corotating interaction regions (CIRs). In the last decade, the unprecedented multi viewpoint observations of the Sun from space, enabled by STEREO Ahead/Behind spacecraft in combination with a suite of observatories along the Sun-Earth lines, have provided much more accurate and global measurements of the size, speed, propagation direction and morphology of CMEs in both 3-D and over a large volume in the heliosphere. Several advanced MHD models have been developed to simulate realistic CME events from the initiation on the Sun until their arrival at 1 AU. Much progress has been made on detailed kinematic and dynamic behaviors of CMEs, including non-radial motion, rotation and deformation of CMEs, CME-CME interaction, and stealth CMEs and problematic ICMEs. The knowledge about SEPs has also been significantly improved**. 2008-11-03, 7 March 2011 , June 30, 2012, 12-14 July 2012, 2012.10.04-05, 8-10 October 2012, 29 May 2013, 2014-06-24**

Relativistic Electron Flux Prediction at Geosynchronous Orbit Based on the Neural Network and the Quantile Regression Method

Hui **Zhang**, Suiyan Fu , Lun Xie , et al.

Space Weather **Volume18, Issue9** e2020SW002445 **2020**

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020SW002445

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Geosynchronous satellites are exposed to the relativistic electrons, which may cause irreparable damage to the satellites. The prediction of the relativistic electron flux is therefore important for the safety of the satellites. Unlike previous works focusing on the single-value prediction of relativistic electron flux, we predict the relativistic electron flux in a probabilistic approach by using the neural network and the quantile regression method. In this study, a feedforward neural network is firstly designed to predict average daily flux of relativistic electrons (>2 MeV), or the expectation of the flux from the probabilistic perspective, at geosynchronous orbit one day in advance. The neural network performs well, with the average root mean squared error (RMSE), the average prediction efficiency (PE), and the average linear correlation coefficient (LC) between observations and predictions reaching 0.305, 0.832, and 0.916, respectively, during the periods of 2011-2017. We then combine the quantile regression method with the feedforward neural network to predict the quantiles of relativistic electron flux by applying a special loss function to the neural network. We use the multiple-quantiles prediction model to predict flux ranges of the relativistic electrons and the corresponding probabilities, which is an advantage over the single-value prediction. Moreover, it appears to be for the first time that the approximate shape of the probability density function of relativistic electron flux is predicted.

Measurements and Simulations of the Geomagnetically Induced Currents in Low-latitude Power Networks During Geomagnetic Storms

J. J. **Zhang** , Y. Q. Yu , C. Wang, D. Du , D. Wei , L. G. Liu

Space Weather **Volume18, Issue8** e2020SW002549 **2020**

https://doi.org/10.1029/2020SW002549

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020SW002549

The issue of geomagnetically induced currents (GICs) on large distance ground-based conductive systems is a global space weather concern nowadays. The low-latitude power grids are becoming more vulnerable to GICs hazards due to their increasing scale and degree of interconnection. Thus GICs measurement and modeling in these systems is of great importance. In this study, we present an analysis of the GICs measurement at a Chinese low-latitude substation during geomagnetic storms. The results show a rough positive correlation between the magnitude of large GIC spikes and dB H /dt spikes. We then built a physical-based model to simulate the GICs at the low-latitude substation during storms. It was found that the simulations capture the main active periods of the GICs during the storms with comparative strength of the measurement. This differs from the previous simulation results for high-latitude regions conducted by Welling et al. (2017). Furthermore, the event analysis method is applied to evaluate the model performance. The results indicate that the physical-based model is more applicable than the persistence model in the prediction of GICs at low-latitude power grids during storms. **9-10 Nov 2004, 7-8 Jan 2015, 17-18 Mar 2015, 14-16 Dec 2015, 19-20 Dec 2015, 30-31 Dec 2015, 6-8 Mar 2016**

Subauroral and polar traveling ionospheric disturbances during the 7-9 September 2017 storms

Shun-Rong **Zhang**, Philip J. Erickson, Anthea J. Coster, William Rideout, Juha Vierinen, Olusegun Jonah, Larisa P. Goncharenko

Space Weather **2019**

https://doi.org/10.1029/2019SW002325

This study provides new scenarios for storm-time traveling ionospheric disturbance (TID) excitation and subsequent propagation at subauroral and polar latitudes. We used ground-based total electron content observations from Global Navigation Satellite System (GNSS) receivers combined with wide field, subauroral ionospheric plasma parameters measured with the Millstone Hill Incoherent Scatter Radar during strong September 2017 geospace storms. Observations provide the first evidence of significant influences on TID propagation and excitation caused by the presence of large subauroral polarization stream (SAPS) flow channels. Simultaneous large and medium scale TIDs (LSTIDS/MSTIDs) evolved during the event in a broad subauroral and mid-latitude area near dusk. Similar concurrent TIDs occurred near dawn sectors as well during a period of sustained southward Bz. MSTIDs at subauroral and mid- latitudes had wave fronts aligned northwest-southeast near dusk, and northeast-southwest near dawn. These wave fronts were highly correlated with the direction of storm-time large zonal plasma drift enhancements at these latitudes. At high latitudes, unexpected, predominant, and persistent storm-time TIDs were identified with 2000+ km zonal wave fronts and 15\% TEC perturbation amplitudes, moving in trans-polar propagation pathways from the dayside into the nightside. This propagation direction in the polar region was opposite to the normal assumption that TIDs originated in the nightside auroral region. Results suggest that significant dayside sources, such as cusp regions, can be efficient in generating trans-polar TIDs during geospace storm intervals.

Introduction to NASA Living With a Star Institute Special Section on Low Earth Orbit Satellite Drag: Science and Operational Impac (**Review**)

Yongliang **Zhang**, Larry J. Paxton and James C. Jones

Space Weather Quarterly v. 15 No. 3, **2018**

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/swq.19

Space Weather, 16, 939–945. https://doi.org/10.1029/2018SW001983

Modeling geomagnetically induced electric field and currents by combining a global MHD model with a local one-dimensional method

Zhang, J. J.; Wang, C.; Tang, B. B.

Space Weather, Vol. 10, No. 0, S05005, **2012**

http://dx.doi.org/10.1029/2012SW000772

Geomagnetically induced currents (GIC) flowing in long conductor systems on the ground are a well-known space weather hazard. We develop a new approach to simulating GICs by combining a global MHD model with a local one-dimensional method. As an example, we apply this approach to model the GIC at the Pirttikoski 400 kV transformer of the Finnish high-voltage power system during the space weather event of 22–23 September 1999. The modeled results can capture the main observational features, and the model performances is better than two GIC persistence models, which demonstrates this promising new approach in GIC forecasting.

Solar cycle variation of the GPS cycle slip occurrence in China low-latitude region

Zhang, D. H.; Cai, L.; Hao, Y. Q.; Xiao, Z.; Shi, L. Q.; Yang, G. L.; Suo, Y. C.

Space Weather, Vol. 8, No. 10, S10D10, **2010**

http://dx.doi.org/10.1029/2010SW000583

Using the Global Positioning System (GPS) cycle slip data detected from the observations of two GPS stations over China low-latitude region from 1999 to 2005, the solar cycle variation of cycle slip occurrence is studied. It is found that the cycle slip occurrence in these two stations varies with solar cycle and shows good temporal correlation; the cycle slip occurs in solar maximum years (1999–2002) much more frequently than that in solar minimum years (2003–2005). In solar maximum years, the seasonal and diurnal dependences of cycle slip occurrence are obvious as shown by previous studies; that is, for seasonal dependence cycle slip mainly occurs in the equinox months and for diurnal dependence cycle slip mainly occurs from 1900 LT to midnight. In solar minimum years, the similar diurnal dependence of cycle slip still exists, nevertheless, the seasonal dependence of cycle slip is not obvious due to small cycle slip occurrence. In the meantime, the spread F occurrence also shows seasonal and diurnal dependence, but there are some differences compared with cycle slip occurrence. During the period from 2000 to 2002, the Q-type spread F mainly occurs in the equinox months; from 2003 to 2005, the Q-type spread F occurs mainly in summer months. As for the diurnal distribution, the Q-type spread F mainly occurs from 2000 LT to sunrise time and lasts much longer than the cycle slip does, and the F-type spread F mainly occurs after midnight and is very different with the cycle slip occurrence. Considering the reasons for cycle slip phenomenon in GPS observations, it is thought that the statistical results of cycle slip occurrence with solar cycle, season, and local time just reflect the temporal distribution of the ionospheric irregularities above a certain intense level over the observing region.

Statistical analysis of corotating interaction regions and their geoeffectiveness during solar cycle 23,

Zhang, Y., W. Sun, X. S. Feng, C. S. Deehr, C. D. Fry, and M. Dryer
J. Geophys. Res., 113, A08106, **2008**
http://dx.doi.org/10.1029/2008JA013095
This is an investigation of the effects of corotating interaction regions (CIRs) in the heliosphere (<1 AU) on geomagnetic disturbances during solar cycle 23 (1996–2005). Three kinds of interplanetary structures, "pure" CIR, interaction of CIR with ICME, and "pure" ICME by transient events, are identified by using the Hakamada-Akasofu-Fry (HAF) solar wind model. Yearly occurrence of 157 "pure" CIRs has a minimum value in 2001 and a peak value in 2003 at the declining phase during the 23rd solar cycle. The maximum correlation coefficient of the daily sum of *Kp* indices between consecutive Carrington Rotations indicates that recurrent geomagnetic disturbances are dominant during the declining phase near solar minimum. Eighty percent of storms that are related to "pure" CIRs belong to weak and moderate storms. The statistical analysis shows that about 50% of CIRs produce classical interplanetary shocks during the descending phase and 89% of the CIR-related shocks are followed by geomagnetic storms. These results demonstrate that CIR-related shock is not a necessary condition for generating a magnetic storm, but most CIR-related shocks are related to a storm. The *Dst* index that corresponds to CIR-related storms has a better linear relationship with IMF *Bz, Ey*, and the coupling function (ε -динамо с учетом меридиональных потоков. Для полученной системы уравнений генерации магнитного поля построено уравнение Гамильтона□Якоби с помощью асимптотического метода, аналогичного методу ВКБ. Это уравнение позволяет аналитически исследовать влияние меридиональных потоков на длительность цикла магнитной активности Солнца и эволюцию волн магнитного поля.

CLEAR Space Weather Center of Excellence: All-Clear Solar Energetic Particle Prediction

Lulu **Zhao**
Space Weather **2023**
https://arxiv.org/pdf/2310.14677.pdf
The CLEAR Space Weather Center of Excellence (CLEAR center) is a five year project that is funded by the NASA Space Weather Center of Excellence program. The CLEAR center will build a comprehensive prediction framework for solar energetic particles (SEPs) focusing on the timely and accurate prediction of low radiation periods (``all clear forecast") and the occurrence and characteristics of elevated periods. This will be accomplished by integrating empirical, first-principles based and machine learning (ML)-trained prediction models. In this paper, the motivation, overview, and tools of the CLEAR center will be discussed.

Current status of CME/shock arrival time prediction **Review**

Xinhua **Zhao** , Murray Dryer
Space Weather Volume12, Issue7 July **2014** Pages 448-469
http://onlinelibrary.wiley.com/doi/10.1002/SWQv11i002/pdf
sci-hub.se/10.1002/2014SW001060 **File**
One of the major solar transients, coronal mass ejections (CMEs) and their related interplanetary shocks have severe space weather effects and become the focus of study for both solar and space scientists. Predicting their evolutions in the heliosphere and arrival times at Earth is an important component of the space weather predictions. Various kinds of models in this aspect have been developed during the past decades. In this paper, we will present a view of the present status (during Solar Cycle 24 in 2014) of the space weather's objective to predict the arrival of coronal mass ejections and their interplanetary shock waves at Earth. This status, by implication, is relevant to their arrival elsewhere in the solar system. Application of this prediction status is clearly appropriate for operational magnetospheric and ionospheric situations including $A->B->C$…solar system missions. We review current empirical models, expansion speed model, drag-based models, physics-based models (and their real-time prediction's statistical experience in Solar Cycle 23), and MHD models. New observations in Solar Cycle 24, including techniques/models, are introduced as they could be incorporated to form new prediction models. The limitations of the present models and the direction of further development are also suggested.

Terrestrial temperature, sea levels and ice area links with solar activity and solar orbital motion

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2023.*
https://solargsm.com/wp-content/uploads/2023/11/zharkova_tsi_nc_form_subm-1.pdf
This paper explores the links between terrestrial temperature, sea levels and ice areas in both hemispheres with solar activity indices expressed through averaged sunspot numbers together with the summary curve of eigen vectors of

the solar background magnetic field (SBMF) and with changes of Sun-Earth distances caused by solar inertial motion resulting from the gravitation of large planets in the solar system. Using the wavelet analysis of the GLB and HadCRUTS datasets two periods: 21.4 and 36 years in GLB, set and the period of about 19.6 years in the HadCRUTS are discovered. The 21.4 year period is associated with variations in solar activity defined by the summary curve of the largest eigen vectors of the SBMF. A dominant 21.4-year period is also reported in the variations of the sea level, which is linked with the period of 21.4 years detected in the GLB temperature and the summary curve of the SBMF variations. The wavelet analysis of ice and snow areas shows that in the Southern hemisphere it does not show any links to solar activity periods while in the Northern hemisphere the ice area reveals a period of 10.7 years equal to a usual solar acitviity cycle. The TSI in March-August of every year is found to grow with every year following closely the temperature curve, because the Sun moves closer to the Earth orbit owing to gravitation of large planets. (solar inertial motion, SIM). While the variations of solar radiation during a whole year have more steady distribution without a sharp TSI increase during the last two centuries. The additional TSI contribution caused by SIM is likely to secure the additional energy input and exchange between the ocean and atmosphere.

Systematic Analysis of Machine Learning and Feature Selection Techniques for Prediction of the Kp Index

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The Kp index is a measure of the mid-latitude global geomagnetic activity and represents short-term magnetic variations driven by solar wind plasma and IMF. The Kp index is one of the most widely used indicators for space weather alerts and serves as input to various models, such as for the thermosphere and the radiation belts. It is therefore crucial to predict the Kp index accurately. Previous work in this area has mostly employed artificial neural networks to nowcast Kp, based their inferences on the recent history of Kp and on solar wind measurements at L1. In this study, we systematically test how different machine learning techniques perform on the task of nowcasting and forecasting Kp for prediction horizons of up to 12 hours. Additionally, we investigate different methods of machine learning and information theory for selecting the optimal inputs to a predictive model. We illustrate how these methods can be applied to select the most important inputs to a predictive model of Kp and to significantly reduce input dimensionality. We compare our best performing models based on a reduced set of optimal inputs with the existing models of Kp, using different test intervals and show how this selection can affect model performance.

Space Radiation and Plasma Effects on Satellites and Aviation: Quantities and Metrics for Tracking Performance of Space Weather Environment Models Review

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https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2018SW002042

The Community Coordinated Modeling Center (CCMC) has been leading community-wide space science and space weather model validation projects for many years. These efforts have been broadened and extended via the newly-launched International Forum for Space Weather Modeling Capabilities Assessment (https://ccmc.gsfc.nasa.gov/assessment/). Its objective is to track space weather models' progress and performance over time, a capability that is critically needed in space weather operations and different user communities in general.

The Space Radiation and Plasma Effects Working Team of the aforementioned International Forum works on one of the many focused evaluation topics and deals with five different subtopics (https://ccmc.gsfc.nasa.gov/assessment/topics/radiation-all.php) and varieties of particle populations: Surface Charging from 10s eV to 40 keV electrons, Internal Charging due to energetic electrons from hundreds keV to several MeVs. Single Event Effects from Solar Energetic Particles (SEPs) and Galactic Cosmic Rays (GCRs) (several MeV to TeVs), Total Dose due to accumulation of doses from electrons (>100 KeV) and protons (> 1 MeV) in a broad energy range, and Radiation Effects from SEPs and GCRs at aviation altitudes. A unique aspect of the Space Radiation and Plasma Effects focus area is that it bridges the space environments, engineering and user communities.

The intent of the paper is to provide an overview of the current status and to suggest a guide for how to best validate space environment models for operational/engineering use, which includes selection of essential space environment and effect quantities and appropriate metrics.

Solar variability manifestations in weather and climate characteristics

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JASTP Volume 182, January **2019**, Pages 217-222
https://www.sciencedirect.com/science/article/pii/S1364682618301469?dgcid=raven_sd_via_email
We discuss the issues of primary importance to understand the nature of climate changes in the 20th century and main physical processes responsible for these changes and present a physical model for the solar activity (SA) effect on climate characteristics. A key concept of this model is the heliogeophysical disturbance effect on the Earth climate system parameters driving the long-wave radiation flux moving away from the Earth out into space in high-latitude regions. We address the solar activity effect on the changes in the temperature of the atmosphere and of the World Ocean. The aa–index of the geomagnetic activity (GA) was used as an SA proxy index. We discuss the results of analyzing the regularities and peculiarities of the tropospheric and sea surface temperature (SST) responses to both separate heliogeophysical disturbances and long-term changes in solar and geomagnetic activity. The structure of the tropospheric and SST temperature responses was shown to feature a spatial time irregularity. We revealed the regions, where long-term SST changes are determined mainly by SA variations.

Prediction Model for Solar Energetic Proton Events: Analysis and Verification
Qiuzhen **Zhong** , Jingjing Wang , Xuejie Meng, Siqing Liu, Jiancun Gong
Space Weather **2019**
sci-hub.se/10.1029/2018SW001915
Solar energetic protons (SEPs) can cause radiation damage to satellites. The Space Environment Prediction Center of China defines the start of an SEP event as the time when three consecutive instances of the 5 min averaged integral flux of >10 MeV protons equal or exceed the 10 proton flux unit threshold. In this study, we analyzed the 5 min averaged soft X-ray flux and the differential and integral proton flux obtained by the Geostationary Operational Environmental Satellites for the period from January 1990 to September 2017 and developed SEP prediction models and their products. The statistical models take one or two data products and the given thresholds as the predictor and predict whether a SEP event will occur or not in the next 24 hours. The quality of the forecast models was measured by comparing the model results against certain verification metrics. Our model taking the products of 5 min averaged integral flux of >10 MeV protons and long wavelength of soft X-ray flux as predictors can provide a probability of detection of 0.80 (152/190), a false alarm ratio of 0.26 (53/205), and an average warning time of 2.6 h for the correctly predicted events. In addition, the model can provide a critical success index of 0.63, a Gilbert skill score of 0.62, and a Heidke skill score of 0.76.
Table 1. SEP events list (1990-2017)

Exploring the potential of microwave diagnostics in SEP forecasting: The occurrence of SEP events
Pietro **Zucca**, Marlon Núñez and Karl-Ludwig Klein
J. Space Weather Space Clim., 7, A13 (**2017**)
https://www.swsc-journal.org/articles/swsc/pdf/2017/01/swsc170001.pdf
Solar energetic particles (SEPs), especially protons and heavy ions, may be a space-weather hazard when they impact spacecraft and the terrestrial atmosphere. Forecasting schemes have been developed, which use earlier signatures of particle acceleration to predict the arrival of solar protons and ions in the space environment of the Earth. The UMASEP (University of MAlaga Solar particle Event Predictor) scheme forecasts the occurrence and the importance of an SEP event based on combined observations of soft X-rays, their time derivative and protons above 10 MeV at geosynchronous orbit. We explore the possibility to replace the derivative of the soft X-ray time history with the microwave time history in the UMASEP scheme. To this end we construct a continuous time series of observations for a 13-month period from December 2011 to December 2012 at two microwave frequencies, 4.995 and 8.8 GHz, using data from the four Radio Solar Telescope Network (RSTN) patrol stations of the US Air Force, and feed this time series to the UMASEP prediction scheme. During the selected period the Geostationary Operational Environmental Satellites (GOES) detected nine SEP events related to activity in the western solar hemisphere. We show that the SEP forecasting using microwaves has the same probability of detection as the method using soft X-rays, but no false alarm in the considered period, and a slightly increased warning time. A detailed analysis of the missed events is presented. We conclude that microwave patrol observations improve SEP forecasting schemes that employ soft X-rays. High-quality microwave data available in real time appear as a significant addition to our ability to predict SEP occurrence. **2012 May 17, 2012 July 07, 2012 July 17, 2012 September 27**
Table 1. Forecast results for each of the SEP events that occurred from November 2011 to December 2012

УНИКАЛЬНАЯ БАЗА ДАННЫХ ТРАНЗИЕНТНЫХ ЯВЛЕНИЙ В КОСМИЧЕСКИХ ЛУЧАХ И МЕЖПЛАНЕТНОЙ СРЕДЕ
Абунин1,2 А.А., Абунина1 М.А., Белов1 А.В., Гайдаш1 С.П.,
Ерошенко1 Е.А., Прямушкина3 И.И., Трефилова1 Л.А.
Астрономия-**2018** Том 2 Солнечно-земная физика – современное состояние и перспективы Стр. 7

ВЛИЯНИЕ КОСМИЧЕСКОЙ СРЕДЫ НА ФУНКЦИОНИРОВАНИЕ ИСКУССТВЕННЫХ СПУТНИКОВ ЗЕМЛИ

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Геомагнетизм и Аэрономия, т. 44, No 4, с. 502-510, **2004** **Текст**

Описана созданная авторами база данных по отказам на 300 космических аппаратах с различными орбитами за период 1971-1994 гг., послужившая основой для статистического анализа влияния окружающей среды на работу спутников. Впервые в анализ включены данные по 49 спутникам серии «Космос». База данных содержит также большой набор суточных и часовых значений параметров космической погоды. Статистический анализ, проведенный по более чем 6000 отказам, позволил получить количественные характеристики связей отказов с факторами космической погоды. В частности, очень интенсивные потоки солнечных протонов (>1000 pfu с энергией >10 МэВ) вызывают почти 20-кратное возрастание числа отказов на высоких полярных орбитах и гораздо менее влияют на геостационарные и низкие полярные орбиты. Повышенные потоки электронов (e>2МэВ) увеличивают число отказов на геостационарных и на низкоорбитальных полярных спутниках, но практически не сказываются на высоких полярных орбитах. Обсуждаются также прямые и косвенные связи между отказами и геомагнитной возмущенностью.

ВЛИЯНИЕ ФАКТОРОВ КОСМИЧЕСКОЙ ПОГОДЫ НА РАБОТУ РАДИОСРЕДСТВ

Review

БЕРНГАРДТ О.И.

СОЛНЕЧНО-ЗЕМНАЯ ФИЗИКА Том: 3Номер: 3 Год: **2017** Страницы: 40-60

В работе проведен обзор влияния факторов космической погоды на работу радиосредств. Обзор основан на работах, монографиях и стратегических научных планах исследования космической погоды последних лет. Основное внимание уделено влиянию ионосферных процессов, обусловленных космической погодой, на распространение радиоволн, в основном коротких. Приведены некоторые примеры такого влияния на основе данных радара ЕКВ ИСЗФ СО РАН на 2012-2016 гг.: ослабление сигналов возвратно-наклонного зондирования во время солнечных вспышек, эффекты перемещающихся ионосферных возмущений различных масштабов в сигналах возвратно-наклонного зондирования, эффекты магнитосферных волн в сигналах ионосферного рассеяния.

ПРОГНОЗ КОСМИЧЕСКОЙ ПОГОДЫ - ПРЕДСТОЯЩИЕ БЕСПОКОЙНЫЕ ГОДЫ?

Владимирский Б.М.

ГиА Том: 118Номер: 2 Год: 2022 Страницы: 34-43

https://elibrary.ru/item.asp?id=48749029

На основании анализа историко-статистических данных XII-XIX вв. установлено, что риск наступления эпизодов социальной нестабильности - бунты, революции - возрастает преимущественно на фазе спада четного и подъема нечетного 11-летних циклов солнечной активности. Вероятность возникновения масштабных вооруженных конфликтов повышается с приближением к максимуму космического цикла длинных волн Кондратьева (около 55 лет). Если эти закономерности реализуются в некоторых регионах, то самым беспокойным годом будет 2024 ± 1 г. Сразу же после предстоящего 11-летнего максимума солнечной активности, около 2026 года, начнется снижение глобальной температуры. Крайнее значение, около 0.30, будет достигнуто примерно к 2035 г. К концу столетия температура восстановится.

Изв. КрАО Том: 118Номер: 2 Год: 2022 Страницы: 34-43

Ранняя диагностика геомагнитных бурь на основе наблюдений систем космического мониторинга

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СЗФ **2018**

Рассмотрена задача ранней диагностики геомагнитных бурь на основе цифровой обработки наблюдений угловых положений центров солнечных корональных выбросов масс, получаемых измерительными системами космического мониторинга.Предложен метод ранней диагностики геомагнитных бурь. Введена функция прогноза расстояния между Землёй и центрами корональными выбросами масс, сформирована процедура принятия решений. Разработан алгоритм диагностики, основанный на минимизации функционала обобщённой триангуляции и оценивании параметров уравнений движения центров корональных выбросов масс. Обеспечено вычисление функции прогноза расстояния и реализованапроцедура принятия диагностического решения. Определена эффективность процедуры принятия решений для алгоритма ранней диагностики геомагнитных бурь.

КОСМИЧЕСКАЯ ПОГОДА: ФАКТОРЫ РИСКА ДЛЯ ГЛОБАЛЬНЫХ НАВИГАЦИОННЫХ СПУТНИКОВЫХ СИСТЕМ **Review**

Демьянов В.В., Ясюкевич Ю.В.

СОЛНЕЧНО-ЗЕМНАЯ ФИЗИКА Том 7 № 2 , **2021**, С. 24–29

https://naukaru.ru/ru/storage/viewWindow/72945

Устойчивость и качество работы глобальных навигационных спутниковых систем (ГНСС) второго поколения (GPS, Galileo, BeiDou/Compass, ГЛОНАСС) и их функциональных дополнений зависят от воздействия экстремальных факторов космической погоды. В обзоре представлены сведения о механизмах воздействия геомагнитных бурь, ионосферных неоднородностей и мощных всплесков радиоизлучения Солнца на сегмент пользователей ГНСС. Представленные сведения подкреплены обзором результатов наблюдений последствий воздействия космической погоды на функционирование ГНСС в 2000–2020 гг. Рассматриваются относительная плотность сбоев измерений радионавигационных параметров и снижение точности позиционирования пользователей ГНСС в режиме двухчастотных измерений и в режиме дифференциальной навигации (Real Time Kinematic, RTK), в том числе при решении задач высокоточного позиционирования (Precise Point Positioning, PPP). Рассмотрена частота появления опасных факторов космической погоды и возможности прогнозирования последствий их воздействия на сегмент пользователей ГНСС. В качестве основных выводов обзора можно выделить следующие: 1) при воздействии экстремальных факторов космической погоды погрешность позиционирования пользователей ГНСС в различных режимах навигационно-временных определений может увеличиваться более чем в 10 раз в сравнении с фоновыми условиями; 2) за последнее десятилетие проведена модернизация космического и наземного сегмента ГНСС, позволившая существенно повысить помехоустойчивость системы в условиях воздействия мощных вспышек радиоизлучения Солнца; 3) существует принципиальная возможность дальнейшего увеличения устойчивости и повышения точности измерения радионавигационных параметров в условиях влияния факторов космической погоды за счет внедрения алгоритмов адаптивной настройки измерителей; 4) в настоящее время остаются нерешенными проблемы контроля целостности системы и доступности требуемых навигационных характеристик с учетом воздействия экстремальных факторов космической погоды. **21 апреля 2002, 28 октября 2003, 20 ноября 2003, 6 декабря 2006, 23-24 сентября 2011, 22 июня 2015, 5-6 сентября 2017**

КОМПЛЕКС ГЕЛИОГЕОФИЗИЧЕСКИХ ИНСТРУМЕНТОВ НОВОГО ПОКОЛЕНИЯ **Review**

ЖЕРЕБЦОВ Г.А.

Солнечно-земная физика. **2020**. Т. 6. № 2 6-18

http://ru.iszf.irk.ru/images/5/50/%D0%96%D0%A1%D0%97%D0%A4_6_1_2020_6-18.pdf

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В статье рассматривается актуальность проблемы неблагоприятных воздействий космических процессов и явлений (факторов космической погоды) на наземную инженерно-техническую инфраструктуру, радиоэлектронные средства, работающие в космосе, и другие объекты.

Анализируется состояние экспериментальной базы в нашей стране и за рубежом для исследований в области физики Солнца, атмосферы и околоземного космического пространства. Обосновывается необходимость создания инструментов нового поколения, разработанных с применением современных инженерных решений и технологий.

Рассмотрен комплекс основных установок и инструментов создаваемого Национального гелиогеофизического комплекса РАН. Сформулированы основные научные направления фундаментальных исследований и прикладные задачи.

РОЛЬ СОЛНЕЧНОЙ АКТИВНОСТИ В НАБЛЮДАЕМЫХ ИЗМЕНЕНИЯХ КЛИМАТА В XX ВЕКЕ

ЖЕРЕБЦОВ Г.А.1, КОВАЛЕНКО В.А.1, КИРИЧЕНКО К.Е.

Геомагн. и аэроном. Том: 57Номер: 6 Год: **2017** Страницы: 687-695

Рассматривается и обсуждается возможный вклад солнечной и геомагнитной активности в изменении характеристик основных компонент климатической системы - океана и атмосферы. Представлены механизмы и модели воздействия солнечной активности на термобарические и климатические характеристики тропосферы. На основе комплексного анализа гидрометеорологических данных показано, что в изменениях температуры тропосферы и Мирового океана наблюдается отклик как на отдельные гелио-геофизические возмущения, так и на долговременные изменения (1854- 2015 гг.) солнечной и геомагнитной активности. Установлено, что климатический отклик на влияние солнечной и геомагнитной активности характеризуется значительной пространственно-временнбй неоднородностью, носит региональный характер и зависит от общей циркуляции атмосферы. Наибольший вклад солнечной активности в изменения глобального климата отмечался в период 1910-1943 гг.

ПРОГНОЗ КОСМИЧЕСКОЙ ПОГОДЫ: ПРИНЦИПЫ ПОСТРОЕНИЯ И ГРАНИЦЫ РЕАЛИЗАЦИИ (ОПЫТ ТРЁХ ЦИКЛОВ)

ИШКОВ В.Н.

Косм. Исслед. Том: 55Номер: 6 Год: **2017** Страницы: 391-398

Все значимые краткосрочные возмущения околоземного космического пространства вызваны исключительно солнечными вспышечными событиями и областями в короне Солнца с открытым в межпланетное пространство магнитным полем (корональные дыры). Вспышечные процессы возникают как следствие взаимодействия новых всплывающих магнитных потоков в пределах активных областей (вспышки) и вне их (выбросы волокон), с уже существующими магнитными полями. Наблюдение за всплытием новых магнитных потоков, оценка их величины и темпа всплытия позволяет прогнозировать солнечные вспышки и выбросы волокон и оценивать степень их геоэффективности. Основными агентами, визуализирующими распространение возмущения от солнечных вспышек и волокон в короне Солнца и в межпланетном пространстве, являются корональные выбросы вещества, характеристики которых в идеале позволяют оценить возможное возмущение геомагнитного поля, возможный рост потоков заряженных частиц больших энергий в ОКП. Для успешного прогноза геоэффективных активных явлений на Солнце и их последствий в ОКП необходимо знать обстановку на Солнце за последние 3 суток, учитывая момент развития и характеристики текущего цикла и эпоху солнечной активности.

ПРОГНОЗ ЭКСТРЕМАЛЬНЫХ СОБЫТИЙ КОСМИЧЕСКОЙ ПОГОДЫ ПО ФЛУКТУАЦИЯМ КОСМИЧЕСКИХ ЛУЧЕЙ

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Косм. Иссл. Том: 60Номер: 2 Год: **2022** Страницы: 105-115

В экстремальных событиях Космической погоды образуются и наибольшие по величине потоки “штормовых” частиц, предваряющих приход ударной волны на орбиту Земли. Именно они представляют наибольшую опасность для систем жизнеобеспечения в верхней атмосфере, в Космосе и на Земле. Проведена заверка результатов прогноза “штормовых” частиц ускоренных ударными волнами по вариациям космических лучей высоких энергий данными измерений на космическом аппарате *ACE*, США. Оценка достоверности прогноза $P \geq 80\%$.

СРЕДНЕСРОЧНОЕ ПРОГНОЗИРОВАНИЕ ПОТОКОВ РЕЛЯТИВИСТСКИХ ЭЛЕКТРОНОВ НА ГЕОСТАЦИОНАРНОЙ ОРБИТЕ ПРИ ПОМОЩИ МАШИННОГО ОБУЧЕНИЯ С ИСПОЛЬЗОВАНИЕМ ДАННЫХ НАБЛЮДЕНИЙ КОРОНАЛЬНЫХ ДЫР

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ГиА Том: 60Номер: 3 Год: **2020** Страницы: 293-304

В работе предложена модель прогноза интегральных суточных потоков (флюенсов) релятивистских электронов (Е > 2 МэВ) внешнего радиационного пояса Земли (РЭ ВРПЗ) на геостационарной орбите с использованием изображений Солнца в ультрафиолетовом диапазоне. Полученные результаты показывают, что точность прогноза потоков РЭ ВРПЗ на трое-четверо суток вперед существенно возрастает при добавлении в обучающие параметры прогнозируемых значений скорости солнечного ветра на околоземной орбите, полученных на основе обработки изображений Солнца в УФ-диапазоне прибором AIA обсерватории SDO.

Развитие мировой сети Службы Солнца и российская сеть

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http://www.gaoran.ru/russian/solphys/2021/gao2021.pdf

Вариации магнитного поля и другие активные процессы на солнце модулируют солнечный ветер и создают переменчивую космическую погоду в околоземном пространстве, а также в окрестностях Луны и Марса – основных целей будущих пилотируемых полётов. Создание моделей краткосрочного и долгосрочного

прогноза космической погоды требует непрерывных наблюдений Солнца в разных диапазонах длин волн. Такие наблюдения могут осуществляться с наземной сети однотипных телескопов с долготным расположением, позволяющим круглосуточные наблюдения Солнца. В настоящее время, существует несколько таких сетей. Сеть солнечных оптических телескопов (Solar Observing Optical Network — SOON) включает три станции расположенных в США (штат Нью Мексико), Западной Австралии, и Италии. Наблюдения включают отождествление и измерение площадей активных областей и их Hα наблюдения. Мониторинг радиоизлучения проводится сетью солнечных радио телескопов RSTN (Radio Solar Telescope Network) расположенных в США (штаты Массачусетс и Гавайи), Западной Австралии, и Италии. Управление сетями SOON and RSTN осуществляется ВВС США. Сеть станций GONG (Global Oscillations Network Group) состоит из шести телескопов, расположенных в США (штаты Калифорния и Гавайи), Западной Австралии, Индии, на Канарских островах, и Чили. Каждая станция создаёт карты изменения Допплеровских скоростей для гелиосейсмологии, продольного магнитного поля, и изображения Солнца в Hα. Управляется сеть Национальной Солнечной Обсерваторией США (NSO). Существует неформальная глобальная сеть Hα телескопов (Global High-Resolution Hα Network). Наблюдения проводятся независимыми обсерваториями и собираются в общую базу данных. Несколько глобальных сетей находятся на стадии разработки: CHAIN (Continuous Hα Imaging Network, Япония), ngGONG (next generation GONG, США), SPRING (Европейский Союз), SOMNET (Solar Activity MOF Monitor, Венгрия).
Ранее в России при поддержке федеральной целевой программе (ФЦП) в период 2008-2014 были созданы прототипы телескопов для наблюдения Солнца, в том числе магнитографы СТОП и патрульные автоматические телескопы. Часть из них, в том числе один магнитограф и автоматические патрульные телескопы, работают и в настоящее время. Таким образом, результат ФЦП оказался положительным. Россия оказалась второй страной в мире, после США, способная проводить прогнозирование КП по схеме SWPC/NOAA на основе своих наблюдений. Однако полностью запустить наблюдательную сеть (Уссурийск, Иркутск, Кисловодск) так и не удалось. Также сейчас появилась необходимость модернизации уже работающих телескопов. В настоящее время необходим новый универсальный телескоп для прогнозирования космической погоды, с условным названием СПОТ (Солнечный патрульный оптический телескоп нового поколения). На основе полученного опыта эксплуатации телескопа-магнитографа СТОП и патрульных телескопов, телескоп СПОТ предназначен для наблюдений магнитного поля на фотосфере и непрерывных наблюдений солнечной активности в хромосферных линиях Hα и Ca II K на полном диске Солнца.
В докладе будут представлены обзор современного состояния наземных сетей для наблюдения Солнца и планы их дальнейшего развития в России и за рубежом.

ВОЗДЕЙСТВИЕ КОСМИЧЕСКОЙ ПОГОДЫ НА НАЗЕМНЫЕ ТЕХНОЛОГИЧЕСКИЕ СИСТЕМЫ **Review**

В.А. **Пилипенко**

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https://naukaru.ru/ru/storage/viewWindow/75304

Предлагаемый впервые в отечественной научной литературе обзор посвящен различным аспектам проблемы воздействия космической погоды (КП) на наземные технологические системы. Особое внимание уделено нарушениям в работе линий электропередач (ЛЭП), железнодорожной автоматики и трубопроводов, вызванным геоиндуцированными токами (ГИТ) при возмущениях геомагнитного поля. В обзоре даны сведения об основных характеристиках вариабельности геомагнитного поля и быстрых вариациях поля при различных проявлениях КП. Излагаются основы моделирования возмущений геоэлектрического поля, основанные на алгоритмах магнитотеллурического зондирования. Рассмотрены подходы к оценке возможных экстремальных величин ГИТ. Собраны сведения об экономических эффектах КП и ГИТ. Рассказано о современном состоянии и перспективах прогноза КП, а также об оценке риска для технологических систем при воздействии ГИТ. Следует подчеркнуть, что хотя в космической геофизике активно разрабатываются различные модели предсказания интенсивности магнитных бурь и вызванных ими геомагнитных возмущений по наблюдениям межпланетной среды, эти модели не могут быть непосредственно применены для предсказания интенсивности и положения ГИТ, так как описание вариабельности геомагнитного поля требует разработки отдельных моделей. Выявление тонкой структуры быстрых геомагнитных вариаций во время бурь и суббурь и вызываемых ими всплесков ГИТ оказалось важным не только с практической точки зрения, но и для развития фундаментальных представлений о динамике околоземного космического пространства (ОКП). В отличие от узкоспециальных работ по геофизическим аспектам вариаций геомагнитного поля и инженерным аспектам воздействия ГИТ на работу промышленных трансформаторов обзор рассчитан на более широкую научно-техническую аудиторию, без потери научного уровня изложения. Иными словами, геофизическая часть написана для инженеров-энергетиков, а инженерная — для геофизиков. Несмотря на явную прикладную направленность рассматриваемых исследований, эти работы не сводятся к чисто инженерному применению результатов космической геофизики для расчета возможных рисков для технологических систем, а ставят и ряд принципиальных научных проблем.

Ground-based Solar Observations for Space Weather Forecasting

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https://arxiv.org/ftp/arxiv/papers/2303/2303.01708.pdf

The possibilities of organizing an observation service for solar activity in order to provide space weather forecasting are considered. The most promising at this stage is the creation of a ground-based observation network. Such a network should include solar magnetographs that provide observation of large-scale magnetic fields of the Sun, and patrol optical telescopes designed to detect coronal mass ejections and solar flares. The data of magnetographic observations provide an assessment of recurrent solar winds. Patrol telescopes operating in continuous mode allow detecting the moments of eruption and determining the parameters of coronal mass ejections at the initial stage of acceleration. The network service can be supplemented with other types of observations in the radio and optical bands. The paper considers the composition of observational tools, as well as methods and models for forecasting.

02.10.2014, 20 февраля 2021

СОЛНЕЧНАЯ АКТИВНОСТЬ, ВАРИАЦИИ ГАЛАКТИЧЕСКИХ КОСМИЧЕСКИХ ЛУЧЕЙ И ГЛОБАЛЬНАЯ СЕЙСМИЧНОСТЬ ЗЕМЛИ

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Выполнен сопоставительный корреляционный анализ с 21 по 24 цикл солнечной активности между числом сильных (магнитуда $M \geq 5.0$) коровых (глубина гипоцентра $0 \leq h \leq 60$ км) землетрясений в году ($N_{EQ/Year}$), отражающим глобальную сейсмическую активность Земли, и суммарным годовым потоком солнечного излучения на длине волны 10.7 см ($F10.7_{Year}$), интегрально характеризующим уровень солнечной активности. Статистически значимый коэффициент линейной корреляции $\rho(N_{EQ/Year}, F10.7_{Year}) = -0.414$. Рассмотрена корреляция между $N_{EQ/Year}$ и среднегодовой вариацией интенсивности потоков галактических космических лучей δ_{Year} на этом же временно́м интервале, при этом $\rho(N_{EQ/Year}, \delta_{Year}) = 0.459$, что позволяет объяснить ~20% изменений $N_{EQ/Year}$ в рамках линейной однофакторной модели изменениями δ_{Year}, и при рассмотрении солнечной активности и интенсивности галактических космических лучей как независимых факторов, формирующих сейсмическую активность Земли, теснота связи между интенсивностью галактических космических лучей и сейсмической активностью Земли оказывается больше, чем между солнечной активностью и сейсмической активностью Земли на изученном интервале времени для массива сильных землетрясений с $M \geq 5.0$...