

Predicting the magnetic vectors within coronal mass ejections arriving at Earth

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Abstract. 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, leading to disruptions to, for example, power grids and satellite navigation. Unfortunately, forecasting magnetic vectors within coronal mass ejections remains 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. 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. It is expected that future statistical work to better quantify the uncertainties may help the heuristic approach of the early forecasting systems used by forecasters.

1. Introduction

CMEs are often observed to have twisted “flux rope” magnetic field structures [Liu *et al.*, 2008; Vourlidas, 2014]. If favourably oriented, these can lead to extended southward excursions of the interplanetary magnetic field (IMF) as the CME passes by, resulting in periods of enhanced reconnection on Earth’s dayside and energy input into the magnetosphere. Draping of the IMF around the CME as it moves through the solar wind may also give rise to southward fields. In contrast, northward-directed fields inhibit reconnection, resulting in a weaker magnetospheric response [Dungey, 1961]. Thus, inferring the direction of the flux rope fields inside a CME before it arrives at Earth would be a major advance in geomagnetic activity prediction.

In addition, the CME’s initial configuration and its interaction with the inhomogeneous ambient solar wind can lead to deformations, rotations, and deflections of the magnetic field, which are difficult to quantify [e.g. Odstreil and Pizzo, 1999; Savani *et al.*, 2010; Nieves-Chinchilla *et al.*, 2012]. Distortions of CMEs have previously been observed by coronagraphs. However, their influence on the magnetic structure is difficult to estimate because the magnetically-dominated regions of CMEs appear as dark cavities within images, such as those seen by the STEREO spacecraft [Howard and DeForest, 2012]. Therefore, a common approach to predicting magnetic vectors within a CME propagating towards Earth is to use solar observations as inputs

into 3D computational simulations. Unfortunately, obtaining realistic magnetic field directions at Earth from such calculations is scientifically challenging and computationally intensive [Manchester *et al.*, 2014].

Thus, models used for routine CME forecasts by various space weather services do not include magnetic structures within the simulated CMEs [Zheng *et al.*, 2013; Shiota *et al.*, 2014, e.g.]. For example, ENLIL models the propagation of CMEs from ~ 20 solar radii (Rs) to beyond Earth at 215 Rs and includes the background solar wind magnetic field. However, the CME is simplified to a high pressure plasma pulse with a size and propagation direction estimated from solar imagery [Zheng *et al.*, 2013]. CME arrival-time predictions from these models provide lead times of $\sim 2 - 3$ days, and their accuracy has been well investigated [Taktakishvili *et al.*, 2010; Colaninno *et al.*, 2013]. In contrast, the important magnetic vector information is only revealed when in situ measurements are made by spacecraft upstream of Earth at the first Lagrangian position (L1) ~ 1 hour prior to the CME arriving at Earth, thereby severely limiting the lead time available for reliable, magnetic field-based, storm warnings.

Difficulties in observationally determining the magnetic profile of a CME arriving at Earth from only solar imagery predominately lie with several complex stages that change the initial solar configuration to the final topological structure at Earth. We suggest that for forecasting purposes, statistically significant predictions can be made by simplifying the complex behaviour to a core set of parameters. In this paper, we highlight three key components as a proof of concept developed to improve the prediction of a storm’s severity: 1. the ubiquitous use of the hemispheric helicity rule to provide a robust initial magnetic configuration at the Sun; 2. a reliable solution to define a ‘volume of influence’ of the CME, within the heliosphere, for which the Earth’s trajectory can be estimated; and 3. incorporating magnetic vectors from a simplified magnetic flux rope model to create a time-series upstream of Earth.

From the analysis of eight Earth-directed CMEs between 2010 and 2014, we conclude that the incorporation of magnetic field vectors in this way can significantly improve geomagnetic forecasts by providing a time-varying magnetic

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profile of the CME. The time varying magnetic profile is then incorporated with an experimental technique to create a time varying Kp index forecast.

2. Solar initiation

The helicity and initial orientation of the magnetic flux rope structure within a CME are inferred from the ‘Bothmer-Schwenn’ scheme. This relates the flux rope properties to sunspots, the solar cycle, and whether the CME originates on the northern or southern solar hemisphere [Bothmer and Schwenn, 1998]. The reliability of this solar hemispheric rule remains controversial. It was only in late-2013 when the probability of a CME’s topology conforming to the hemispheric rule was re-confirmed to be $\geq 80\%$ [Wang, 2013; Hale, 1925]. Thus, the initial helicity and field structure of CMEs can be inferred from this scheme with a reliability that is likely to be $\sim 80\%$.

The hemispheric solar source region of the CME is identified from solar observations. Figure 1 displays a 171Å image from the AIA instrument onboard the SDO spacecraft taken at 20.14 UT on 7th January, 2014. This event has a controversial arrival time and in situ profile, and has been chosen to highlight the complexity in forecasting processes. Under the Bothmer-Schwenn scheme, the topological structure of this CME is estimated to have a right handed chirality. Ordinarily, a CME is linked to a single active region where the standard Bothmer-Schwenn scheme should be applied. However in cases such as this January 2014 event, the magnetic loop structure before eruption has a leading negative polarity spanning over two active regions. Thus, a South-West-North, ‘SWN’, flux rope field direction from southern hemisphere of solar cycle 23 under the Bothmer-Schwenn scheme is appropriate.

Harra *et al.* [2007] highlighted the complexity of trying to estimate the orientation of an interplanetary CME from simple solar observations. The work displayed that two CMEs released in November 2004 from a similar source location can have drastically different final topology. However, this case study event follows the Bothmer-Schwenn scheme if the adjustment described above is made to account for the different polarity of the active region’s leading edge (between AR10695 and AR10696).

By incorporating simpler CMEs that are released from a single active region with an appropriate adjustment for connected active regions, we can begin to generate more reliable predictions. In this article, a total of eight events are investigated with 2 events following the more complicated connected active region scenario (October 2012 and January 2014). Further details of all the estimated magnetic field profiles and modelled Kp values are displayed in the appendix.

3. remotely sensed evolution

Since deflections, rotations and other interactions may occur during CME propagation to Earth, the initial Bothmer-Schwenn configuration is adjusted using coronagraphic data from the STEREO and SOHO missions. The final tilt and source region of the magnetic flux rope, after which radial propagation is assumed [Nieves-Chinchilla *et al.*, 2013], is estimated using the graduated cylindrical shell (GCS) model [Thernisien *et al.*, 2009], when the CME reached 15Rs. Figure 2 displays images from the COR2 instruments onboard the two STEREO spacecraft (A and B) and the LASCO instrument onboard SOHO that are used to triangulate the CME structure. Where three well-separated observations exist, the GCS model provides relatively well-constrained estimates of the orientation and size of the CME without any ambiguity [Liu *et al.*, 2010a; Rodriguez *et al.*, 2011].

The outputs from the GCS model along with estimates of the average CME size [Yashiro *et al.*, 2004] are used to

create a ‘volume of influence through which the CME will propagate into the heliosphere. The shaded region in Figure 1 displays the projection of this ‘volume of influence’ onto the Sun, suggesting that the Earth grazed the northern edge of this case study event.

Any uncertainty in the inferred CME orientation is likely to have only a minimal effect on the predicted magnetic field vectors since it is likely to be eclipsed by the larger uncertainties arising from estimating the magnetic field strength and the assumption of a symmetric cylindrical flux rope, as explained below. The coronagraph images show how the coronal magnetic loops seen in SDO have been deflected to the south west (Figure 1). Here, we use coronagraphic imagery to estimate the final CME radial trajectory but future work could attempt to increase prediction lead times by, for example, incorporating CME deflections by coronal holes [Cremades and Bothmer, 2004; Mäkelä *et al.*, 2013].

A CMEs ‘volume of influence’ is defined as the volume the CME is expected to traverse as it propagates through the heliosphere. A projection of this volume onto the Sun’s surface is displayed as the overall highlighted area in Figure 1. The projected area is calculated from the ‘shadow of the CME that is assumed to be cylindrical in shape with circular cross-section. Two parameters (flux rope axis length and flux rope width) are required to estimate the projected area. The axis length, shown as a dashed curve on Figure 1, is estimated from the half angle, α_{haw} , given by half the angular width of the CME in a direction parallel to the GCS model axis. The projected width of the CME transverse to this axis is assumed equal to the average CME width estimated from statistical studies [Nieves-Chinchilla *et al.*, 2013].

The shortest (perpendicular) distance between the Earth’s projected location and the flux rope axis is indicated on Figure 1 with a blue curve. Normalising this to the total perpendicular distance to the flux rope outer edge (flux rope radius) gives a quantity that is correlated with the impact parameter (Y0) which is a key parameter for in situ flux rope modellers. The theoretical correlation used in this study for the impact parameter is displayed in Figure 3; the Earth’s projected arc distance is displayed in solar radii. This theoretical function is justified by using a simple linear correlation between the Earth’s distance and Y0 for the inner core region surrounding the flux rope axis (inner highlighted area in Figure 1). The outer area is correlated with a trigonometric sine function and is designed to physically represent the distortions to the idealised flux rope that occur during propagation as well as possible draping of the surrounding solar wind magnetic field outside the actual flux rope structure. These distortions to the flux rope are sometimes termed ‘pancaking’ with a recent study suggesting the inner core of a CME is likely to maintain a quasi-cylindrical structure while the outer structure may become severely deformed by the ambient medium [Démoulin and Dasso, 2009; Savani *et al.*, 2013a].

For the case of the January 2014 event, draping of the surrounding solar wind magnetic field is likely to account for significant portion of the measured terrestrial disturbance due to Earth’s trajectory through the outer northern edge. As a first principle, the field rotation from a draped magnetic field as measured from a 1-D spacecraft trajectory can be modelled with the minimal rotations created from a large impact parameter modeled flux rope described below. For cases as extreme as this, a forecast system that generates a subtle field rotation may be considered more appropriate than generating a ‘missing-Earth’ scenario, but extensive statistical analysis will be required to minimise uncertainty for such cases.

4. in situ flux rope

To generate an estimate time-series of the magnetic vector direction passing over a fixed point such as L1, we must employ a methodology to create a 1-D (spacecraft) trajectory through a theoretical structure, and to define the start time of the object at this fixed point.

4.1. time of arrival

To improve the time of arrival prediction of a CME is beyond the scope of this work, and several advances on this topic have been performed. Currently there are several procedures to calculate the speeds of remotely-observed CMEs, quantify their deceleration, and forecast their speeds upstream of Earth at L1 [see further literature within, e.g. *Owens and Cargill, 2004; Colaninno et al., 2013*]. We choose to assume a simple average of the measured CME speed close to the Sun as determined by the NOAA Space Weather Prediction Center (SWPC) and the predicted speed at Earth. In the case of the 7th January, 2014 event, this gives a CME speed of 1300 km/s and a predicted arrival time of 8th January, 21.45 UT. By combining this information with the flux rope model described below, a time-series of magnetic vectors (Figure 5 red curves) is created.

In order to compare the accuracy of the modeled magnetic vector time-series with data and test the technique in the ‘research domain’, we manually adjust the arrival time of the model fit to the best guess estimate within the L1 data. The field rotations between the model estimate and data and then manually inspected. The full list of eight events displaying the magnetic field rotation in spherical coordinates are displayed in figure 8. Spherical coordinates are used over the cartesian system as the orientation components remain independent of the magnetic field strength component. The uncertainties and variety of techniques to estimate the field strength are described below.

However, for a readily implementable process for estimating the magnetic vectors in advance, different forecasting systems can simply employ their best estimate of the arrival time.

4.2. Flux rope model

The configuration of the magnetic flux rope is calculated by assuming a constant-alpha force-free (CAFF) flux rope [*Zurbuchen and Richardson, 2006*] and a cylindrical geometry locally around the Earths predicted trajectory through the CME. Previously, triangulation of the CME direction from remote sensing have shown to provide adequate information as to the expected structure arriving at L1 [*Liu et al., 2010b*]. However a grad-shafranov reconstruction technique used by *Liu et al. [2010b]* would not be appropriate in creating a model to estimate the structure. Future work may consider implementing a more complex model that better represents the distortions occurring to a CME at L1 [e.g. *Marubashi, 1997; Hidalgo et al., 2002; Owens et al., 2006*].

The magnetic vectors generated along the Earths trajectory from a CAFF flux rope model is created from the MHD momentum equation under magnetostatic equilibrium; which can be reduced to $\mathbf{j} = \alpha\mathbf{B}$. A solution to this equation can be used to generate a cylindrical magnetic flux rope with circular cross section, with the components of the magnetic field vector expressed by Bessel functions, and α commonly set to 2.41 *Savani et al. [2013b]*. Future work can consider reducing α as a simple solution to potential flux erosion occurring to the CME during propagation [*Ruffenach et al., 2012*].

The projected axis onto a 2D plane of the CME is provided by a single angle orientation (ϕ) estimated from GCS model. However, the component of the flux rope axis parallel to the radial direction is estimated theoretically, by measuring the shortest distance between the Earth trajectory through the CME away from the CME nose, L_n . In

practice, this was performed by measuring half the length of the flux rope axis (R_{ax}) and the length between the flux rope axis centre and the position where the Earth perpendicular position (Figure 1, blue curve) meets the flux rope axis (D_E); thereby defining, $L_n \equiv D_E/R_{ax}$. $L_n = 0$ represents the case where the CME nose is propagating directly towards Earth, and there is no radial contribution to the flux rope axis. However when $L_n = 1$, the flux rope axis is entirely radial in direction, as might be the case when the Earths trajectory is along a CME leg. Figure 4 displays how the radial contribution is estimated from an angular value (λ) that varies between 0° (CME nose) and 90° (CME leg) in a scheme similar to that used by *Janvier et al. [2013]*. Both ϕ and λ are used to create a 3D flux rope axis direction.

The magnitude of the magnetic field along the central flux rope axis is assumed in this case study to be 18.0 nT. This is calculated by assuming the maximum estimated magnetic field strength within the plasma pile-up region simulated by the WSA-ENLIL+Cone model (10.3nT) corresponds to the magnetic field strength at closest approach within the flux rope structure. The impact parameter obtained using the volume of influence (set at 0.91 for the January 2014 event) is then used to estimate the maximum field strength along the central flux rope axis. In effect, this technique estimates the $|\mathbf{B}|$ of a CME from a correlation of the inner heliospheric CME velocity and a simulated background solar wind field strength driven by magnetograms.

The flux rope axis direction, chirality, magnetic field magnitude and impact parameter provide a complete set of parameters to generate a time series of magnetic vectors along a theoretical Earth trajectory. The estimated Earths trajectory through the CME is quasi-invariant to any variations that are parallel to the flux rope axis. This is because the simplistic model is an axis-symmetric cylinder. The small adjustment that does occur is accounted for by a small adjustment to the radial component of the CME axis direction.

4.3. Magnetic field Strength

The uncertainty in the predicted Kp index was estimated by varying the field strength over the range $|\mathbf{B}| = 18.0_{-1\sigma}^{+2\sigma}$, where $= 6.9\text{nT}$ [*Lepping et al., 2006*], recalculating the magnetic vectors for each field strength, and estimating Kp. The uncertainty in field strength represents the statistical average from 82 flux rope fittings estimated between 1995-2003.

The field strength is inferred from a model currently used for forecasting by CCMC, so this method could be implemented using existing forecasting capabilities. In the future, other methods whose uncertainties have not yet been statistically quantified might be used, for example estimating the poloidal and total flux content of a CME from flare ribbon brightening [*Longcope et al., 2007*]; flux rope speed and poloidal flux injection to estimate field strength [*Kunkel and Chen, 2010*]; using radio emissions from the CME core [*Tun and Vourlidas, 2013*]; and using the shock stand-off distance from MHD observations which has recently shown the possibility of estimating the field strength upstream of a CME [*Savani et al., 2011; Poomvises et al., 2012; Savani et al., 2012*].

There are also processes that can influence the accuracy of the predicted fields, in particular the interaction of CMEs during passage from the Sun to the Earth [*Shen et al., 2012*]. As an example, two CME events launched in quick succession were detected as a single strong event within in situ data and displayed in panel C of the figures (8-9) in the Appendix. In the interim, an experienced observer may be able to manually adjust the computational models in response to such unusual situations in a heuristic manner used by forecasters.

5. Kp estimate

Having inferred the rotating magnetic field vectors near the Earth, a function is required to couple the solar wind to the magnetosphere. Many functions that couple the solar wind to a wide variety of magnetospheric activity have been proposed in the past, often incorporating the magnetic field orientation. A recent study suggests that one parameter correlates best with 9 out of 10 indices of terrestrial activity [Newell *et al.*, 2007]. This parameter, $d\Phi/dt$, represents the rate magnetic flux is opened at the magnetopause and is defined as

$$d\Phi/dt = v^{4/3} |\mathbf{B}|^{2/3} \sin^{8/3}(\theta_c/2) \quad (1)$$

where v is the velocity of the solar wind; $|\mathbf{B}|$ is the magnetic field magnitude; and the IMF clock angle is defined by $\theta_c \equiv \tan^{-1}(By/Bz)$. The correlation coefficient of $d\Phi/dt$ with the Kp index is $r = 0.76$; Kp is the global magnetospheric index often used by forecasters to indicate the severity of a space weather event. The estimated magnetic field time series is used to calculate a theoretical magnetic flux rate. A Kp prediction is generated by the empirical correlation

$$Kp = 9.5 - e^{A-B(d\Phi/dt)} \quad (2)$$

where $A \equiv 2.17676$, and $B \equiv 5.2001 \times 10^5$ with the velocity and magnetic field measured in km/s and nT, respectively. The Kp predictions are easily converted to an official NOAA geomagnetic storm size measured on a scale between G1 to G5 by a linear mapping of the Kp values¹.

For the purpose for ascertaining the effect of our magnetic vector predictions on the Earth's Kp index, we will use the average CME velocity as measured from the Omni (Ace and Wind) data sets at L1 (see figure 6). The reason for implementing the observed velocity from L1 is a simple one; we wish to understand and isolate the effects of the predicted magnetic vectors without prejudice from uncertain estimates of arrival time or velocity predictions. There are many attempts to improve both of these predictions parameters in the current literature. We expect that the operational forecasting processes that estimate the time-of-arrival and velocity can later be included to understand the overall Kp prediction capabilities. Infact, ensemble analytics would become most appropriate once all components are included in the forecast process to better quantify the final uncertainty [e.g. Owens *et al.*, 2014].

Quantifying the uncertainty in this experimental Kp forecast is best achieved by testing the effects of varying the maximum magnetic field strength and the associated velocity within the forecasted CME. Uncertainty in the field strength represents the largest obstacle to replicating the in situ field vectors and providing a reliable Kp forecast. However, the velocity estimate also has a significant impact of the predicted Kp values using the equations above.

For the purposes of providing an early lead-time estimate of the magnetic vectors arriving at L1, we can estimate the field strength by implementing the current process used at the Community Coordinated Modeling Center (CCMC) based at NASA Goddard whereby estimates of the maximum field strength and velocity at L1 are determined from the plasma pile-up region ahead of a CME using the WSA-ENLIL+Cone model. The standard deviation of a CMEs field strength ($\sigma = 6.9nT$), is then used to estimate the uncertainty in the Kp forecast.

As ENLIL does not include CME magnetic fields; only the magnetic structure of the ambient solar wind is included in the model, ENLIL cannot provide any forecasts of the magnetic field vectors inside CMEs that are impacting Earth.

Instead, Space Weather Research Center (SWRC) hosted at the CCMC use a simple but arbitrary process: Using magnetic field strength from ENLIL in the compressed sheath material ahead of a CME, they assume that the field with this strength constantly pointing West, or South during the passage of the CME, and estimate the expected Kp for each case (with the Southwest direction used as an average estimate). Essentially the variations in the field strength estimated from this method attempts to simplify the variety in observations that are caused by the momentum of the CME and the different background solar wind conditions. The Kp forecast issued by SWRC is then the range between these extreme cases, with the highest Kp prediction originating from a southward field as shown in Figure 6 and 9. Thus without the CME direction or an estimate of how the field may vary in time, SWRC are unable to estimate which part of the CME, if any, would contribute the most to being geoeffective. Therefore this contributes to an uncertainty in time for the onset of a variety geo-effective processes.

6. Discussion and Conclusions

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 have been investigated. The predicted magnetic vectors for these events between 2010 and 2014 are displayed in Figure 8, along with the measured L1 in situ data. The angular rotation (B_ϕ and B_θ) in the predicted magnetic field closely follows the broad rotational structure seen within the in situ data. For the events investigated, it has been noticed that if the overlying magnetic field arcade displayed in solar imagery (e.g. within 171Å AIA) traverses two active regions in close proximity, an adjustment to the standard scheme is required. In particular, if the solar arcade is between two active regions, the leading polarity is reversed and the initial magnetic structure is defined by the Bothmer-Schwenn scheme from the previous solar cycle [e.g. as shown in the case study by Harra *et al.*, 2007]. The scenario of this more complex behaviour is shown in the case study event of this article (January 2014, panel G in Figures 7-9), as well as in an event on October 2012 (Figure 7-9, panel F). Therefore, we suggest that the ubiquitous use of the Bothmer-Schwenn scheme with a simplistic flux rope model is capable of generating a zeroth-order characterisation of the rotating magnetic field topology with a flux rope CME.

In order to create this proof-of-concept, several assumptions and simplifications have been made. This is both a strength for the technique being computationally fast, as well as a weakness for the simplifications being unable to always capture the detailed nature of a complicated geomagnetic storm. A detailed statistical investigation is therefore required to further understand the probability distribution of accurate forecasts versus false positives.

Differences between the predicted and actual trajectory of Earth through a CME may affect the inferred magnetic field vectors and hence the terrestrial impact of the CME. Furthermore, a significant number of CMEs detected in situ do not have a clear flux rope-like signature, perhaps due to the trajectory passing near the edge of the interplanetary CME [Zurbuchen and Richardson, 2006; Vourlidas *et al.*, 2013] causing a significant number of false positives if only a cylindrical flux rope field is assumed [Lepping *et al.*, 2005].

Figure 8 also illustrates the limitations of a symmetrical flux rope model, which is frequently highlighted by a variety of in situ models, in that the model field strength are by definition stronger near the center of the flux rope whereas the observed fields occasionally deviate from this pattern. As an example, panels (a), (e) and (f) display the strongest

field near the CME leading edge or sheath, which sometimes occurs when a fast CME compresses against the solar wind ahead.

Figure 8&9 compares the magnetic field and Kp prediction of the new model with measured data and early forecasts made by NOAA space weather prediction center (SWPC) and the Community Coordinated Modeling Center (CCMC) based at NASA Goddard. SWPC issues the official US space weather predictions. Their current procedure is to: 1. Release a geomagnetic watch notice after a solar eruption is observed, i.e. 36-72 hrs prior to expected storm arrival; 2. Send out a warning 1hr prior to storm onset using data from ACE spacecraft at the L1 point to formulate a robust Kp prediction based on established relations between the solar wind parameters and Kp; and 3. Provide Alerts in a now-casting/real time format during the geomagnetic storm using a real-time proxy of the official Kp index. SWPC also publishes routine 3-day Kp forecasts based on a heuristic approach that is heavily dependent on the skill and personal experience of the on-duty forecaster, for example, in interpreting ENLIL simulation results and incorporating knowledge of historical events.

NASA's Goddard Space Flight Center (GSFC) Space Weather Research Center (SWRC) hosted at the CCMC employs more experimental forecasting procedures using the latest scientific techniques that have only recently been deployed in an operational setting. CCMC/SWRC are tasked with addressing the space weather needs of NASA's robotic missions through experimental research forecasts, notification and analysis. For example, an experimental method to forecast Kp using $d\Phi/dt$, based on equation 2 is now in use, and uncertainties in Kp forecasts using the maximum field strength are being estimated [Romano et al., 2013]. CCMC also gathers predictions from researchers around the world² in order to understand the strengths and limitations of the different forecasting techniques they are using. The notifications that CCMC release are for internal use only.

The implementation of this proposed time-varying magnetic field prediction as a component within a heuristic approach is expected to qualitatively aid space weather forecasters, and provide scientific insight by statistically quantifying the terrestrial response for future events.

Appendix A: Eight CME events

The complete results from all eight events are displayed on figures 7, 8 and 9. The figure descriptions are replicated from earlier figures of the case study event of January 2014 described throughout the article.

A1. Appendix

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Notes

1. http://www.swpc.noaa.gov/NOAA_scales/
2. <https://kauai.ccmc.gsfc.nasa.gov/SWScoreBoard/>

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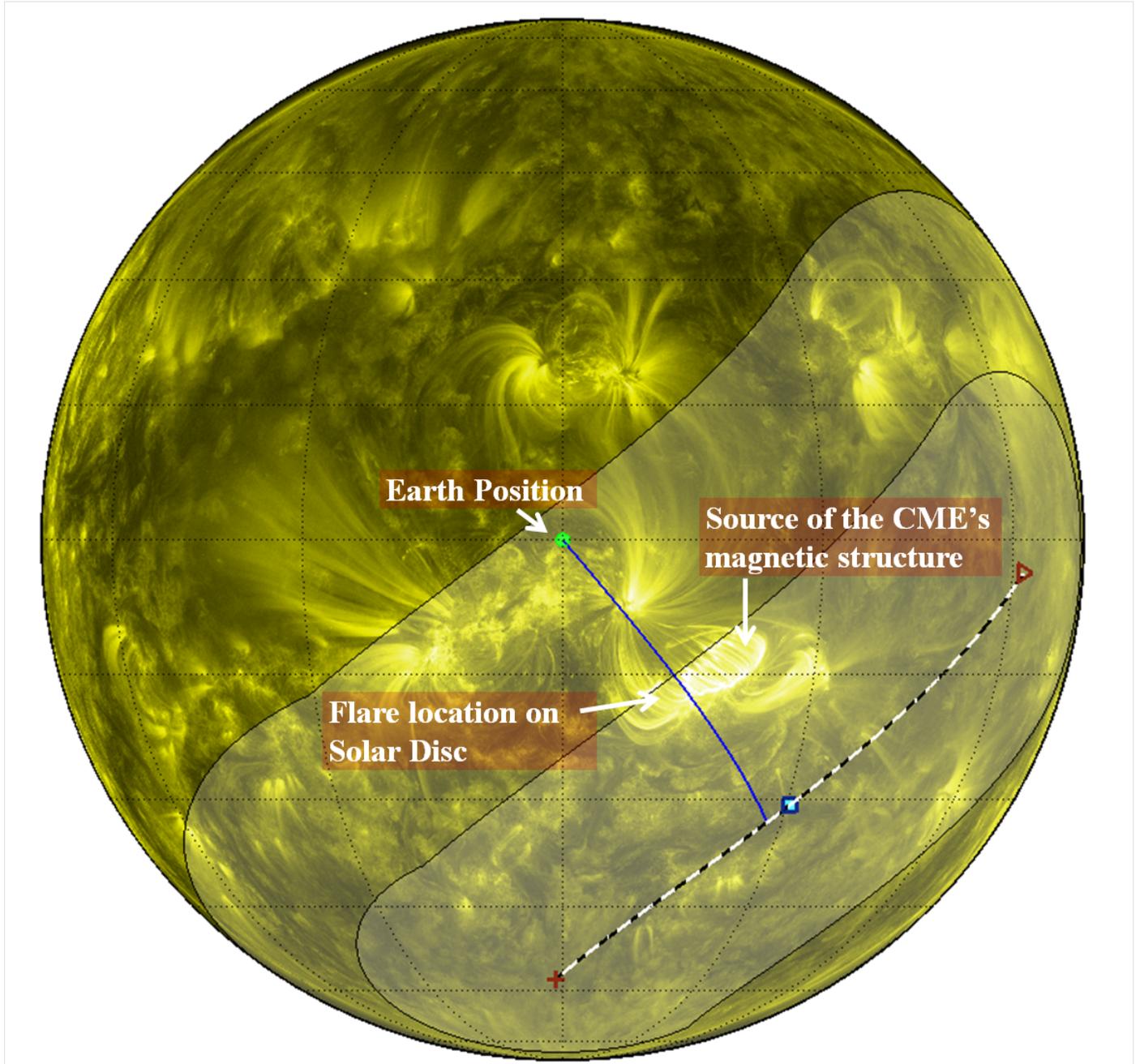


Figure 1. Solar source of the 7th January 2014 eruption. The Sun is shown as a 171 (Fe IX/X) image from the AIA instrument onboard the SDO spacecraft taken at 20.14 UT before the propagation of the coronal mass ejection (CME). The extent of the axis of the CME magnetic structure is indicated by the dashed curve, displaying a southward deflection from the flare location. The center of influence onto the heliosphere from the CME is shown with a blue square. The volume of influence onto the heliosphere from the CME is shaded, suggesting that the Earth only grazed the northern edge of the CME. The perpendicular distance of the Earth from the CME axis is shown in blue.

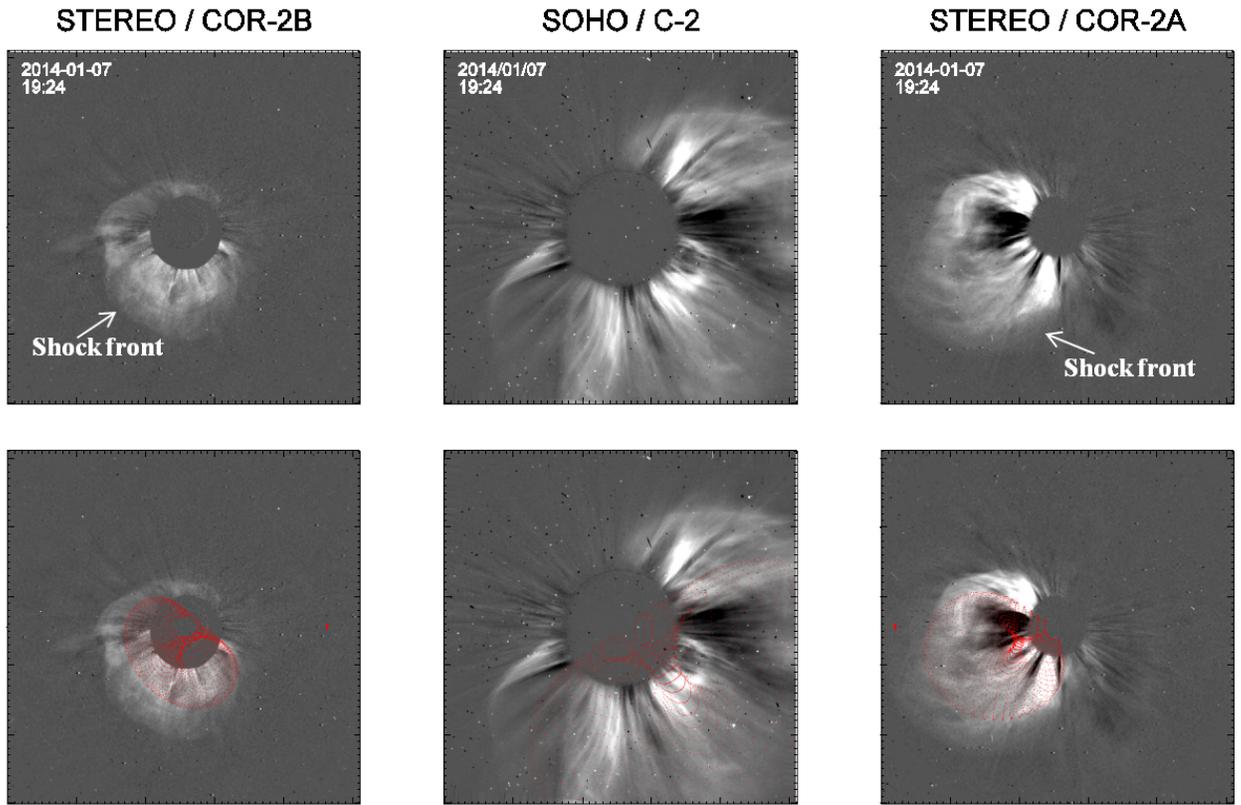


Figure 2. The evolution of the 07 January 2014 CME event from three vantage points. The graduated cylindrical shell model to estimate the topological structure of the event is shown in red. A transition layer ahead of the magnetic structure indicates the distance to the shock wave driven ahead.

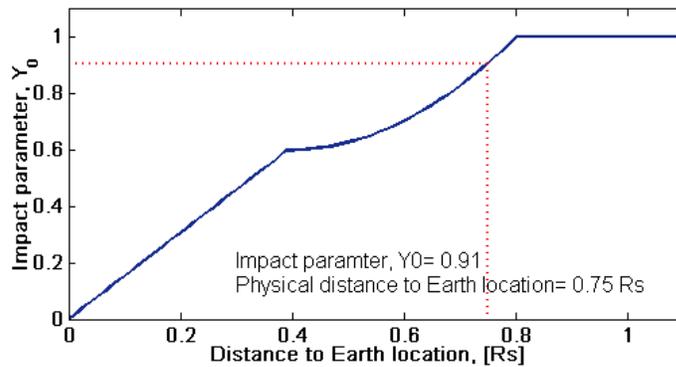


Figure 3. An empirical model comparing the CME axis to Earth distance with a theoretical magnetic structure length. The January 7, 2014 event is shown to graze the outer edge of the magnetic structure, with a normalised impact parameter of $Y_0=0.91$.

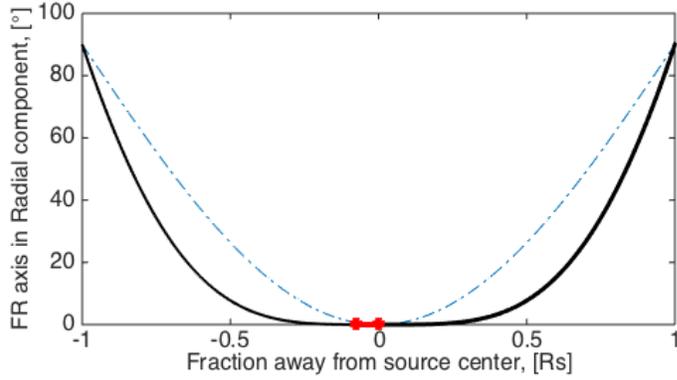


Figure 4. An empirical model to estimate the radial component of the flux rope axis direction (λ). The relative distance of Earth impact and the flux rope nose is shown as the red line. The flux rope axis direction is assumed to be perpendicular to the radial at the nose and parallel to the radial (90°) at both footpoints.

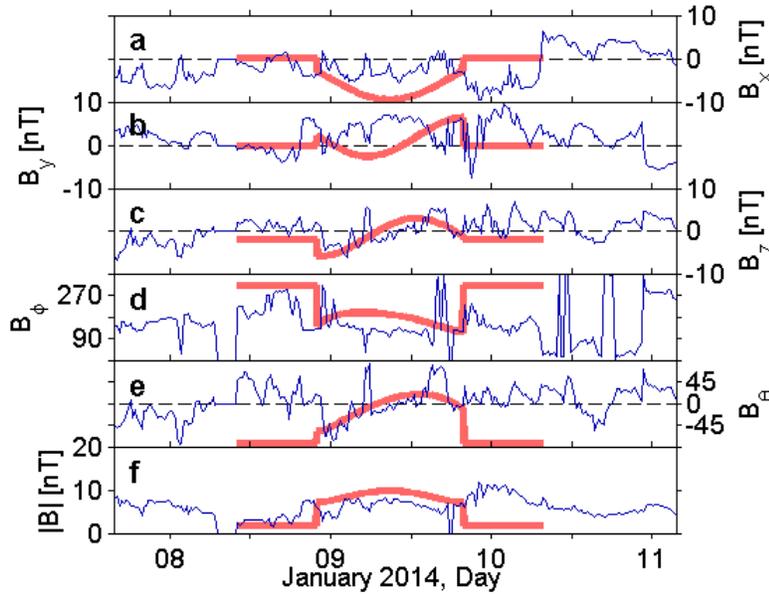


Figure 5. Magnetic vectors from the L1 vantage point upstream of Earth for the arrival of the CME. The magnetic field from the OMNIWeb dataset is shown in GSE components (a-c), and spherical coordinates (d-f). The red curves overlaid represent the forecasted magnetic vectors at Earth.

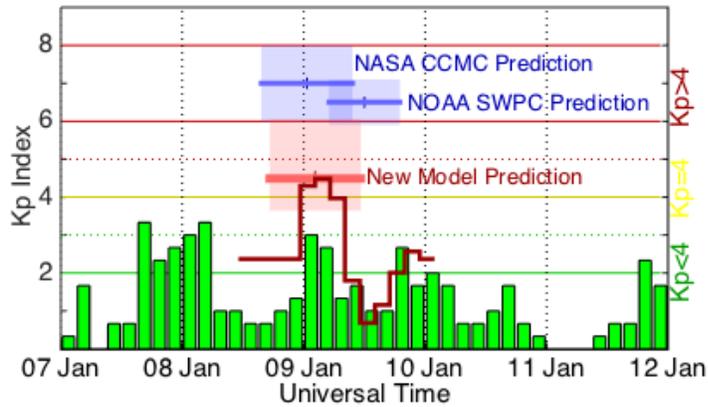


Figure 6. Kp index measuring the Earth's response to the passage of the CME. The red curve displays the forecasted Kp values using the estimated magnetic vectors within the CME. The uncertainty in the maximum forecasted Kp (red shaded region) is estimated by varying the magnetic field magnitude. The blue horizontal bars represent the forecasted Kp values released by NASA CCMC and NOAA SWPC team; the red bar represents the improved results of the new model presented here. The shaded region surrounding the forecast bars represent the forecasted uncertainty range. The actual variation in Kp is shown in green.

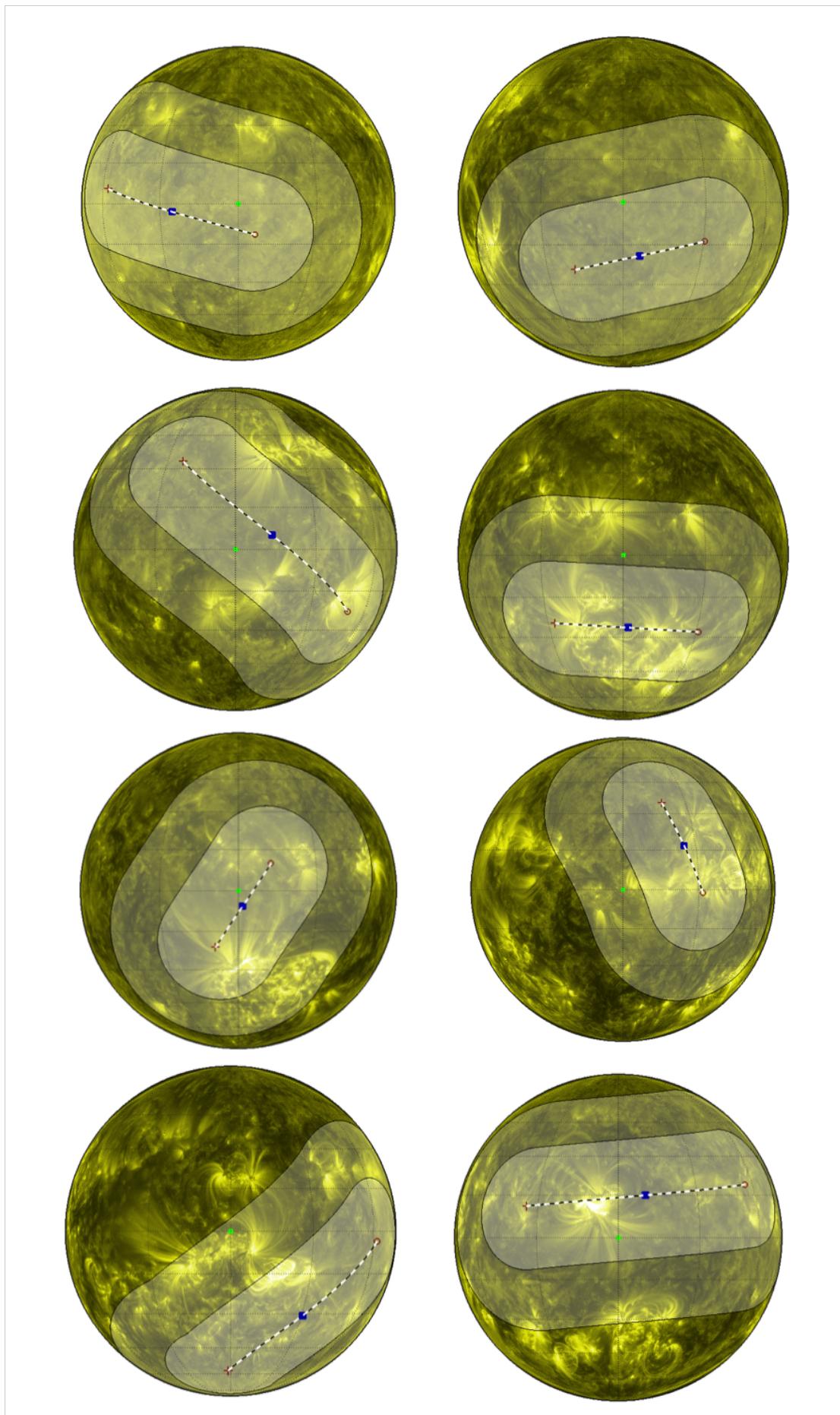


Figure 7. Solar source of 8 CME eruptions between 2010 and 2014. The Sun is shown as a 171 (Fe IX/X) image

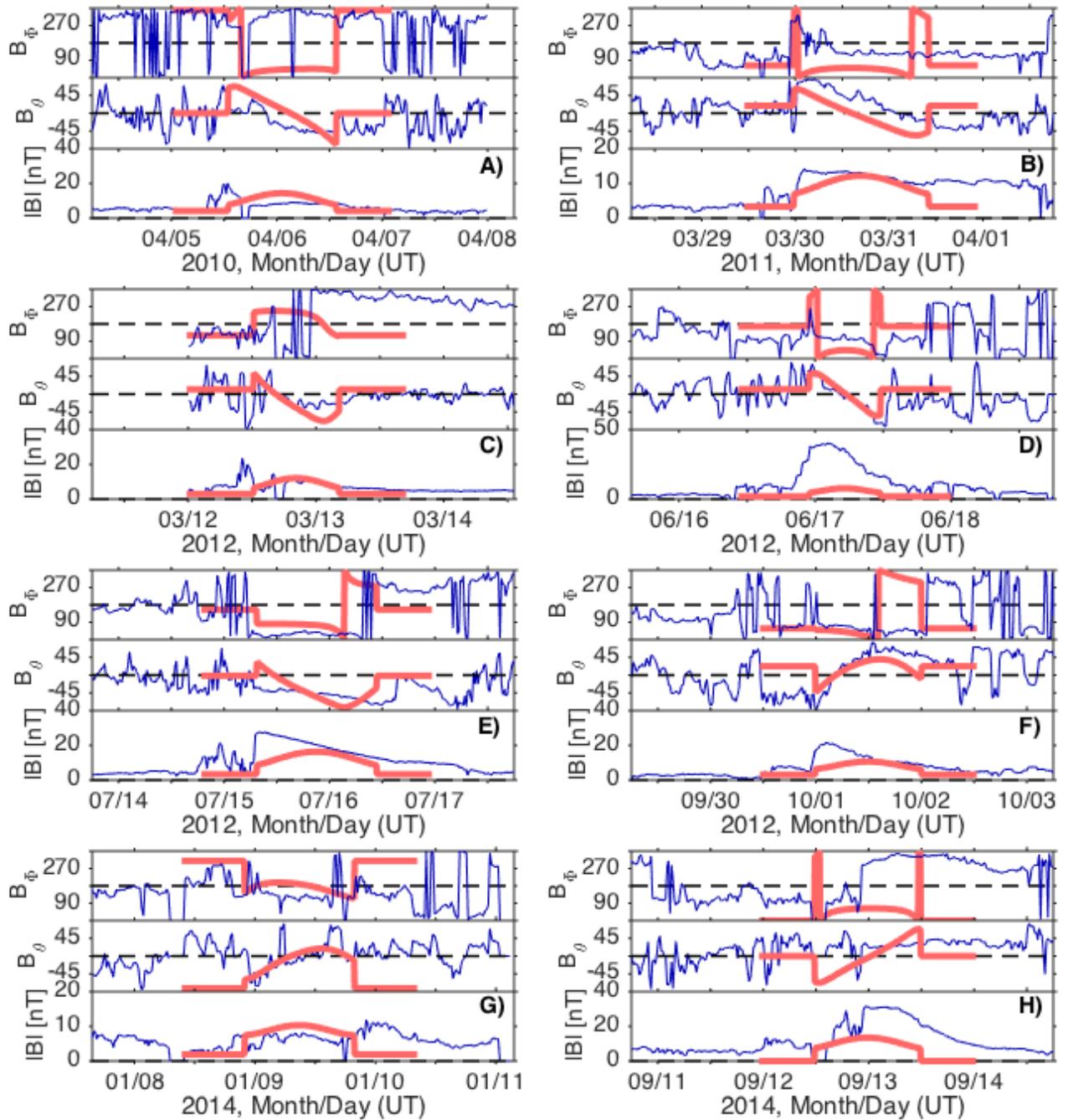


Figure 8. Predicted (red) and observed (L1; blue) magnetic vectors for 8 CME events, where \mathbf{B}_θ is the angular magnetic field direction out of the Sun-Earth plane.

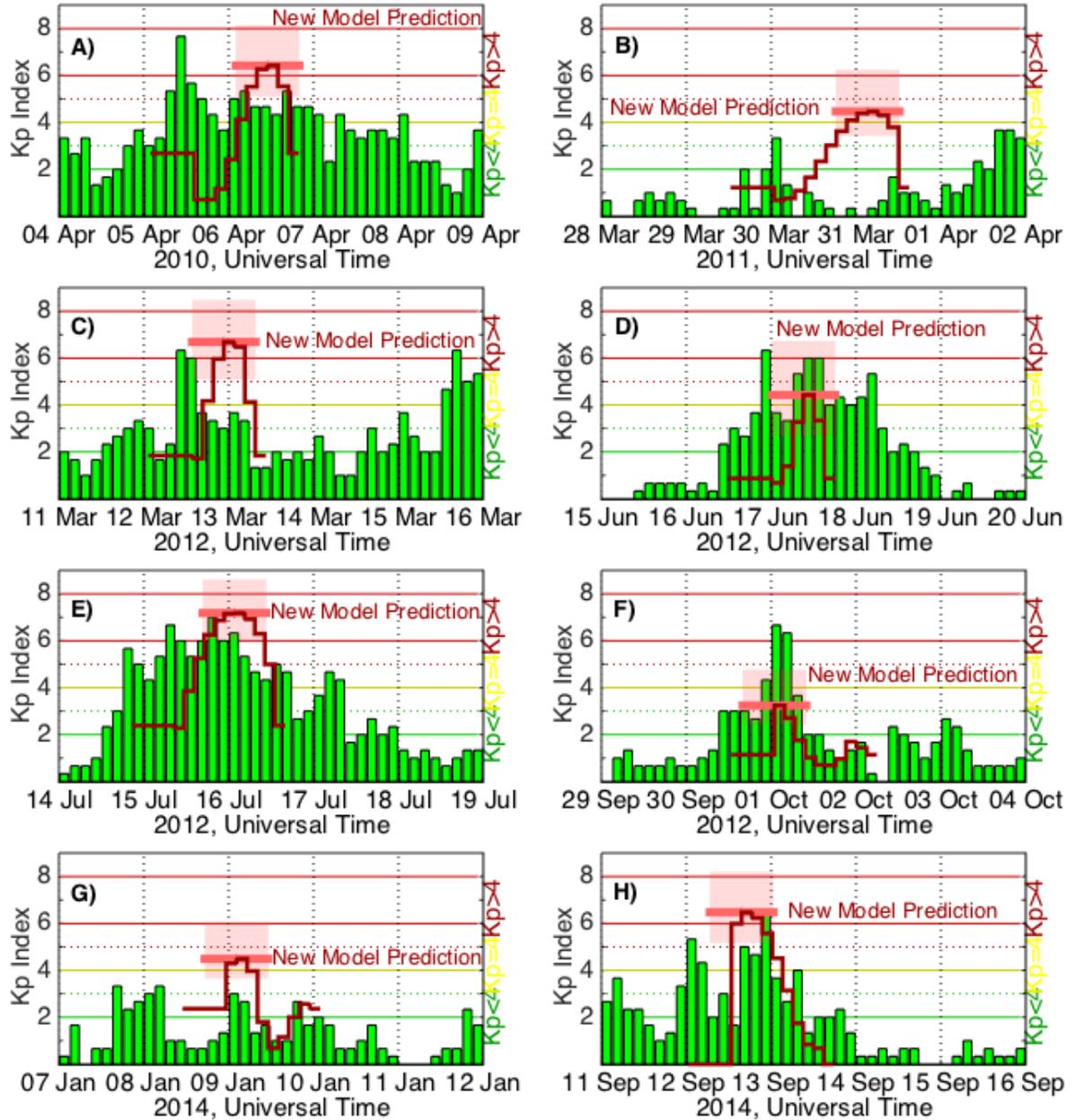


Figure 9. Estimated (red) and observed (green) Kp index for 8 CME events, using the same analytical techniques used to create figure 6.