Validation of the coronal mass ejection predictions at the Earth orbit estimated by ENLIL heliosphere cone model

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[1] Modeling is an important tool in understanding physical processes in the space weather. Model performance studies evaluate the quality of model operation by comparing its output to a measurable parameter of interest. In this paper we studied the performance of the combination of the halo coronal mass ejection (CME) analytical cone model and ENLIL three-dimensional MHD heliosphere model. We examined the CME arrival time and magnitude of impact at 1 AU for different geoeffective events, including the October 2003 Halloween Storm and the 14 December 2006 storm CMEs. The results of the simulation are compared with the ACE satellite observations. The comparison of the simulation results with the observations demonstrates that ENLIL cone model performs better compared to reference mean velocity and empirical models.

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1. Introduction

[2] Scientific models are becoming more and more important tools in understanding physical processes in the solar system. Models often provide a global view of a studied phenomenon that is not available using only satellite or ground observations. Models are used for space weather operators' applications and for space weather forecasting. Therefore, it is essential that the scientific community, operational users, and model developers are aware of model capabilities and limitations. One of the ways of measuring model validation is the metrics analysis, standardized, repeatable comparison of model output to a measurable parameter of interest. The result is expressed as a skill score, a single number, which measures the performance of a model against some reference model, on the basis of modeling of one particular output parameter. Such studies provide continuous feedback to the model developers and encourage further modeling improvement. Metrics analyses are setting benchmarks for the current state of a model and thus is a tool for tracing model progress over time. They also give information about the usefulness of a model upgrade. By having a single number like a skill score to characterize a model, it is easy to compare the performance of different models with similar output. Finally, metrics studies provide information about the usefulness of a model for operations and thus are of particular importance to space weather operators.

[3] In this work we studied the performance of the ENLIL cone model in modeling the propagation of coronal mass ejections (CME) in the heliosphere. The ENLIL cone model has two components (1) cone model for halo CMEs, an analytical method to determine the angular width, propagation orientation and radial velocity of halo CMEs, developed by *Xie et al.* [2004] and (2) the ENLIL heliosphere model, a time-dependent 3-D MHD model of the heliosphere, developed by D. Odstrcil [see, e.g., *Odstrcil and Pizzo*, 1999; *Odstrcil et al.*, 2004]. The results of the simulation are compared with the ACE satellite observations at L1 and a metrics analysis is performed.

[4] A CME is an ejection of material from the solar corona that can be detected remotely with a white light coronagraph. When the CME reaches the Earth as an ICME (interplanetary CME), it may disrupt the Earth's magnetosphere, compressing it on the dayside and extending the nightside tail. The most severe geomagnetic storms are caused by CME events [*Gosling*, 1993]. CMEs can result in damage to satellites, disruption of radio

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transmissions, damage to electrical power transformers and power outages. That is why knowing for example the arrival time of CMEs at the Earth accurately is of crucial importance in predicting space weather.

[5] There have been extensive observational as well as theoretical studies of CMEs in relation to their space weather implications in the recent decade. *Berdichevsky et al.* [2000] studied interplanetary shock statistical properties and their drivers, including solar transients (i.e., CMEs). *Gopalswamy et al.* [2001] developed an empirical model predicting 1 AU arrival times of CMEs. The model is based on an effective interplanetary acceleration that CMEs experience as they propagate from Sun to 1 AU and the primary input is the initial speed of white light CMEs obtained using coronographs. The model results are in reasonable agreement with observations for high speed CMEs. *Gopalswamy et al.* [2005] extended their empirical model to the prediction of the arrival times of the interplanetary shocks. *Xie et al.* [2006] improved input to the empirical model of *Gopalswamy et al.* [2005] by using the cone model method to determine the CME radial velocity. Recently, *Kim et al.* [2007] evaluated the model using 91 interplanetary 64 shocks at 1 AU examining ACE and WIND satellite data. In a number of papers [e.g., *Fry et al.*, 2003; *Oler*, 2004; *Dryer et al.*, 2004; *Smith et al.*, 2005; *McKenna-Lawlor et al.*, 2006], the authors studied the performance of three different CME and shock propagation models, Shock Time of Arrival model (STOA), Interplanetary Shock Propagation model (ISPM), and Hakamada-Akasofu-Fry version 2 model (HAFv2), in forecasting shock arrival times for hundreds of events, including the extreme events of the October–November 2003 "Halloween epoch." STOA, ISPM and HAFv2 models use initial shock speed derived from metric type II radio observations (together with soft X-ray data and solar image data). HAFv2 is the only one of these three that models the variable background solar wind. In all these modeling studies the average error or root mean square error of the ICME shock arrival times to the Earth was 10 or more hours.

[6] Recently, *Wu et al.* [2007] used new hybrid code, combining HAFv2 and 3-D MHD simulation, to study the ICME from the 12 May 1997 solar event. *Toth et al.* [2007] performed sun-to-thermosphere simulation of the 28–30 October 2003 storm with the Space Weather Modeling Framework (SWMF), and *Lugaz et al.* [2007] also using SWMF studied CME events of 24 November 2000. The importance of MHD simulation of CME propagation, is that MHD modeling enables prediction of magnetospheric parameters, as it is done, e.g., by *Toth et al.* [2007].

[7] In this paper we present the results of the ENLIL cone model for 14 CME events and compare them to ACE observations. We focus on two parameters, the arrival time of the CME shock and the magnitude of the CME impact on the magnetosphere. The magnitude of the CME impact is characterized by the magnetospheric magnetic field magnitude needed to stop the CME mass flow. The corresponding magnetopause standoff distance is also calculated. These are two of the most important features for the space weather information users and operators. Another important parameter in this regard is the Bz component of the interplanetary magnetic field, but for the moment ENLIL model does not take into account the realistic complex magnetic field structure of the CME magnetic cloud, so we do not discuss this subject in the presented paper. We use the version of the ENLIL model available at the Community Coordinated Modeling Center at NASA/GSFC.

2. Brief Description of the Halo CME Cone Model and ENLIL Heliosphere Models

[8] *Zhao et al.* [2002] were the first to propose the cone model approximation to determine CME geometric and kinematic parameters. They assumed that a CME propagates with nearly constant angular width in a radial direction and that the expansion is isotropic. On the basis of this work, *Xie et al.* [2004] developed an analytical method for determining the parameters of halo CME, angular width of the cone, propagation orientation and radial speed, using coronagraph images. We use the method developed by *Xie et al.* [2004] in this paper. From Large Angle and Spectrometric Coronagraph (LASCO) C3 coronagraph images we determined CME parameters for 14 halo CME events chosen according to the criteria described below, in the beginning of section 3.

[9] These parameters are used as input to the ENLIL heliosphere model to study the CME propagation out to the ACE location at L1 point. ENLIL is a time-dependent 3-D MHD model of the heliosphere [*Odstrcil and Pizzo*, 1999]. It solves equations for plasma mass, momentum and energy density, and magnetic field, using a Total-Variation-Diminishing Lax-Friedrichs algorithm. Its inner radial boundary is located beyond the sonic point (where the solar wind flow becomes supersonic), typically at 21.5 solar radii. ENLIL can accept boundary condition information from the Wang-Sheeley-Arge (WSA) coronal model [*Arge and Pizzo*, 2000]. WSA models the global magnetic field between the solar surface and a bounding spherical surface, where the magnetic field is assumed to be radial. The photospheric magnetic field is determined from synoptic magnetogram data. WSA computes the solar wind speed at the bounding surface using an empirical relationship. ENLIL applies this WSA output at its inner boundary and propagates the solar wind, including the CME, throughout the heliosphere.

[10] In ENLIL, the CME as a plasma cloud has a uniform velocity. We assumed the cloud's density to be four times larger than the ambient fast solar wind density-density ratio factor, df = 4, by default. The temperature is assumed to be the same. Thus, the plasma cloud has about four times larger pressure than the ambient fast wind. The CME cone model is based on observational evidence that CME has more or less constant angular diameter in corona, being confined by the external magnetic field, so

Table 1. List of the CME Events Studied and the Results for Shock Arrival Time Errors[a]

Event	Date	Start (LASCO)	POS Speed at 20 R_s (LASCO) (km/s)	Observed Transit Time (hours)	V_r Cone Model (km/s)	Δt_{err} ENLIL (hours)	Δt_{err} Reference Model (V_{ref} = 850 km/s) (hours)	Δt_{err} ESA (hours)
1	9 Aug. 2000	1630	720	49	960	4	−1	1
2	29 Mar. 2001	1030	957	38	913	7	10	16
3	6 Apr. 2001	1930	1215	39	1570	−6	9	−12
4	9 Oct. 2001	1130	811	52	1297*	−5	−4	−16
5	17 Nov. 2001	0530	1350	60	934*	−9	−12	−6
6	18 Mar. 2002	0330	971	58	971	−11	−10	−7
7	15 Apr. 2002	0400	731	52	736	−1	−6	10
8	17 Apr. 2002	0830	1198	48	1134	−3	0	−8
9	16 Aug. 2002	1230	1447	53	1249*	−10	−5	−15
10	24 Aug. 2002	0130	1992	57	915	−5	−9	4
11	28 Oct. 2003	1130	2268	19	2752*	1	29	−3
12	29 Oct. 2003	2100	1519	20	2048*	6	28	1
13	25 Jul. 2004	1500	1359	31	1289	9	17	2
14	13 Dec. 2006	0300	1573	35	2170	−5	13	−16
Average absolute						5.9	10.9	8.4

[a]Start (LASCO) means UT of the corresponding date, when the CME is first seen in LASCO C2 coronograph image. POS means plane of sky projection. V_r is the radial velocity, obtained using the cone model method of *Xie et al.* [2004]. Here Δt_{err} means arrival time error. The error in negative if the observed shock arrival was later than model predicted and is positive in the opposite case. Values with asterisks are taken from the paper by *Xie et al.* [2006].

that CME does not expand in latitude in the lower corona, but expands in interplanetary space because of the weaker external field. This is naturally a simplification, but launching of an overpressured plasma cloud at 21.5 R_s, roughly represents CME eruption scenario [see, e.g., *Odstrcil et al.*, 2004].

[11] In the simulations presented here, ENLIL uses the following grid 258 × 30 × 90, where 258 is the spatial resolution in radial direction (range from 0.1 AU to 2 AU), 30 is the angular resolution of the latitude (perpendicular to the ecliptic plane, range from −60° to +60°), and 90 is the angular resolution of the longitude (range from 0° to 360°). The spatial resolution used is rather coarse, resulting in simulations that use less time and computing resources, although this is achieved at the expense of the time resolution at 1 AU and corresponding smoothing of the CME originated shock.

[12] The temporal resolution (time step of the output) was approximately 7 min. Run execution time length for these parameters is approximately 2 hours on a 4 processor machine, which is much faster than real time and is a very good characteristic for forecasting purposes.

3. Simulation Results: Shock Arrival Time

[13] The halo CME events that we studied are listed in Table 1. Table 1 shows the event number and the dates of the events are given. Table 1 also shows the CME start UT from the LASCO catalog (to the nearest 0.5 hours). In addition, Table 1 gives the plane of sky projection velocity (in km/s) at 20 solar radii from the LASCO catalog, the observed transit time (in hours) of the interplanetary shock associated with the CME event, and the CME radial velocity estimated using the method of *Xie et al.* [2004] and used in the ENLIL simulation (the values with asterisk are taken from the paper by *Xie et al.* [2006]).

[14] These halo CME events are chosen from the CME catalog (http://cdaw.gsfc.nasa.gov/CME_list), using the following criteria: (1) clear LASCO/C3 images to enable good determination of cone model parameters using the cone model method of *Xie et al.* [2004]; (2) corresponding clear shock arrival time observed in the ACE satellite data to facilitate comparison with the observations; and (3) estimated initial plane of sky velocities greater or equal to 700 km/s, because fast CMEs are the most important ones from the point of view of space weather effects.

[15] We compared the CME shock arrival times predicted by our ENLIL cone model simulations to the observed shock arrival times. The prediction errors

$$\Delta t_{err} = t_{enlil}^{arr} - t_{obs}^{arr} \quad (1)$$

for each of the events are plotted in Figure 1 (red squares).

[16] The error is negative when ENLIL predicted a shock arrival time earlier than the observed shock arrival time, and is positive for late ENLIL prediction. In this set of 14 modeled cases, there are more earlier predictions (9 out of 14) than late predictions. Earlier arrival errors are, on the average, larger than late prediction errors. Table 1 shows the values of the ENLIL shock arrival prediction errors rounded to the nearest of 0.5 hours under the heading "Δt_{err} ENLIL." The average absolute error for the set of 14 events is approximately 5.9 hours. The average of the earlier arrival prediction errors is −6.1 hours, and average of the late arrival prediction errors is 5.4 hours.

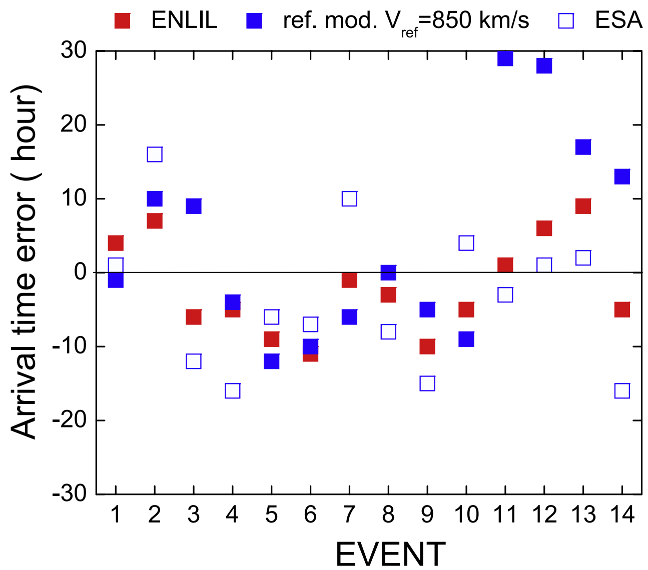

Figure 1. Arrival time errors for the 14 CME events listed in Table 1. ENLIL, red squares; reference model (V_{ref} = 850 km/s), blue squares; ESA, white squares.

[17] To evaluate the ENLIL cone model performance for the shock arrival times, it is useful to compare the simulation results to the results of a reference model. The simplest reference model is propagation of the CME shock with some constant velocity. Taking the mean of initial plane of sky projection velocities for approximately 320 halo CMEs listed in the SOHO/LASCO catalog (http://cdaw.gsfc.nasa.gov/CME_list/) for the period of years 1996–2007, we obtained V_{ref} = 850 km/s. The corresponding transit time from the Sun to the ACE position is approximately 48 hours. The corresponding arrival times for each of the 14 events are taken as the reference model arrival times. The corresponding values of arrival time errors are listed in Table 1 under the heading of "Δt_{err} Reference Model." The average of absolute values of these errors is approximately 11 hours. In Figure 1 the reference model errors are presented as blue squares. ENLIL does a better job in 9 out of the 14 cases, and for 5 events, the reference model gives better prediction.

[18] We also compared the ENLIL cone model results to the results of the empirical shock arrival model (ESA) of *Gopalswamy et al.* [2005]. In accordance with *Xie et al.* [2006], we used estimated radial velocities (Table 1) as input to the empirical equation (11) from *Xie et al.* [2006] to calculate the shock transit times for the cases we analyze in this paper. The resulting values of the arrival time errors are given in Table 1 under the heading "Δt_{err} ESA." The cases marked by asterisk were calculated by *Xie et al.* [2006]. In Figure 1, the ESA model errors are plotted as white squares. The ENLIL cone model, shown by red squares, does a better job in 8 out of the 14 cases and in 6 cases the ESA model gives a better prediction.

[19] We can introduce a parameter characterizing relative performance of ENLIL with respect to these two models

$$R = 1 - \left|\Delta t_{err}^{enlil}\right| \Big/ \left|\Delta t_{err}^{ref,ESA}\right|. \quad (2)$$

In Figure 2 the value of R for ENLIL and the reference model V_{ref} = 850 km/s is shown as blue squares, and R for ENLIL and ESA model as white squares.

[20] In Figure 2, R = 0 means the ENLIL and the reference model give the same error for this event, R = 1 that ENLIL error is zero, positive R means that ENLIL error is smaller, while negative R means that ENLIL error is larger than error of the reference model. We can introduce analog to skill score of ENLIL performance with respect to the reference model, by using the average absolute error for the 14 studied cases

$$SkSc = 1 - \left\langle\left|\Delta t_{err}^{enlil}\right|\right\rangle \Big/ \left\langle\left|\Delta t_{err}^{ref,ESA}\right|\right\rangle. \quad (3)$$

This yields $SkSc$ = 0.46 and $SkSc$ = 0.3 for the reference model V_{ref} = 850 km/s and the ESA model correspondingly. So, we can make an overall conclusion that ENLIL cone model performs better than the reference and empirical models for shock arrival time prediction for most of the 14 fast CME events studied.

4. Magnitude of Impact and Magnetopause Standoff Distance

[21] Besides CME arrival time, there is another parameter that is very important for the space weather forecasters and operators: the magnitude of the impact of the

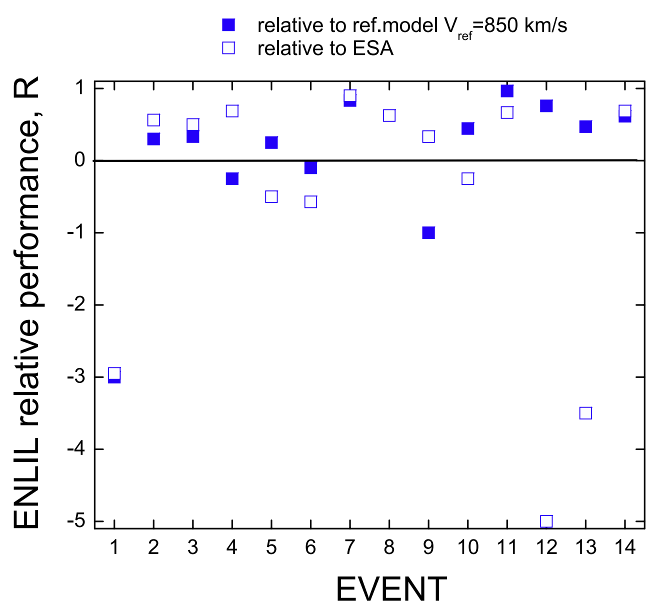

Figure 2. The parameter R, characterizing the relative performance of the ENLIL cone model and the reference model (V_{ref} = 850 km/s; blue squares) and ESA model (white squares).

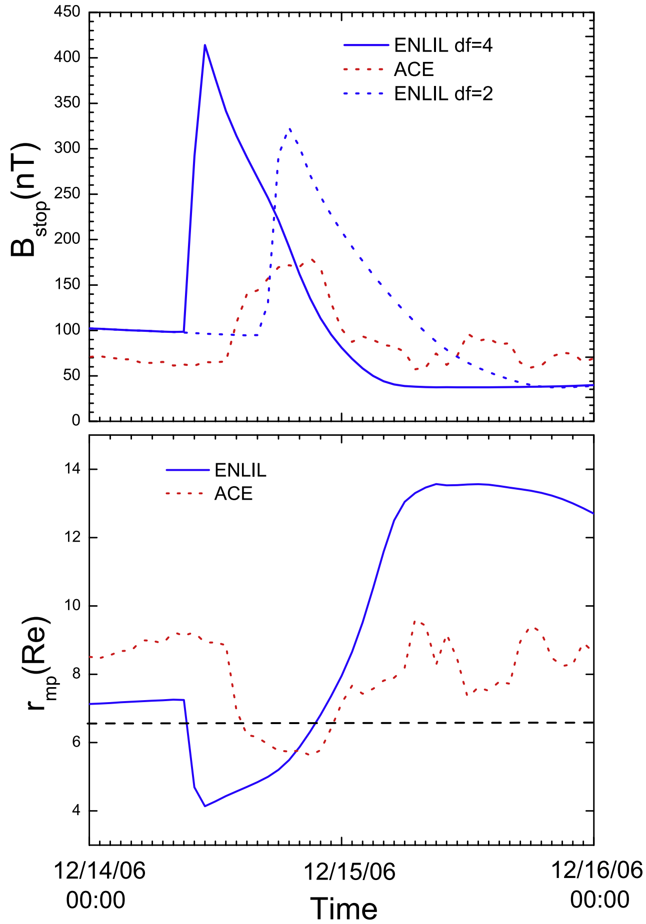

Figure 3. (top) The evolution of the magnetic field B_{stop} that would stop the solar wind (dynamic) pressure calculated from the equation (4) for the 13 December 2006 CME. The 2-day time interval around the shock arrival time is shown. The blue solid line is the ENLIL calculations, using the density factor df = 4, that is used throughout all the simulation. The blue dashed line represents ENLIL calculations using df = 2. The red dashed line shows ACE measurements. The magnetic field values are in nT. (bottom) The evolution of the magnetopause standoff distance corresponding to the B_{stop} calculated if the Earth's magnetic field is assumed to be a dipole for the same event. The blue line is the ENLIL calculations, and the red line is the ACE measurements. The distance is shown in Earth radii R_E. The dashed black line marks the geosynchronous orbit radius 6.6 R_E.

CME on the magnetosphere. We measure this parameter by the degree of the deformation of the Earth's magnetosphere due to the interaction with the CME. It is natural to assume that the physical quantity mostly responsible for the strength of the impact of the CME on the magnetosphere is a dynamic pressure of the solar wind. The magnetic field that would be required to "stop" the solar wind stream can be estimated from the equation given by *Spreiter et al.* [1966]

$$Knm_pV^2 = B_{stop}^2/2\mu_0, \quad (4)$$

where K is a constant that characterizes the degree of reflection of the solar wind stream from the current sheath boundary, n and V are the solar wind number density and plasma velocity respectively, m_p is the proton mass and B_{stop} is the corresponding magnetosphere magnetic field. In ideal case of completely "elastic" reflection $K = 2$, and $K = 1$ for "inelastic" reflection. In the case of high Mach number solar wind, $K \simeq 0.881$ [*Spreiter et al.*, 1966], and we will use this value for K in our analysis.

[22] This equation yields the following expression for the magnetic field:

$$B_{stop} = V\sqrt{1.762nm_p\mu_0}. \quad (5)$$

In Figure 3 (top) we show the evolution of B_{stop} inferred from the model (blue solid line) and observational values at the ACE location (red dashed line) for the 2 day interval around the CME shock arrival time for the 13 December 2006 CME event. As we can clearly see, ENLIL (solid blue line) overestimates the CME ram pressure impact. This happens mainly because of the overestimation of the number density of the arriving CME material, while velocity is predicted with much better accuracy. Thus a second run was made for this case using a lower density ratio factor (df = 2). This is shown by the blue dashed line and will be discussed below.

[23] We can characterize the anticipated response of the Earth's magnetosphere to the CME impact in another way. If we assume that the magnetic field close to the Earth is a dipole, $B = B_0(R_E/r)^3$, where $B_0 = 3.11 \times 10^4$ nT and R_E is the Earths radius, then inserting $B = B_{stop}$ into this equation will give an approximate expression for the magnetopause standoff distance

$$r = \left(B_0/B_{stop}\right)^{1/3}R_E. \quad (6)$$

The Figure 3 (bottom) displays the evolution of the standoff distance for the 13 December 2006 CME event estimated by ENLIL (blue solid line). The standoff distance corresponding to the actual ACE measurements is shown too (red dashed line). The dashed black line marks the geosynchronous orbit radius 6.6 R_E. By overestimating the ram pressure impact, the ENLIL cone model pushes the magnetopause closer to the Earth than would be expected from the ACE measurements of the solar wind ram pressure.

[24] In Figure 4 (top) we show the maximum values of modeled the B_{stop} and those inferred from ACE observations for the 14 CME events we studied. Figure 4 demonstrates that ENLIL cone model overestimates the ram pressure impact for all the events (there is no ACE density

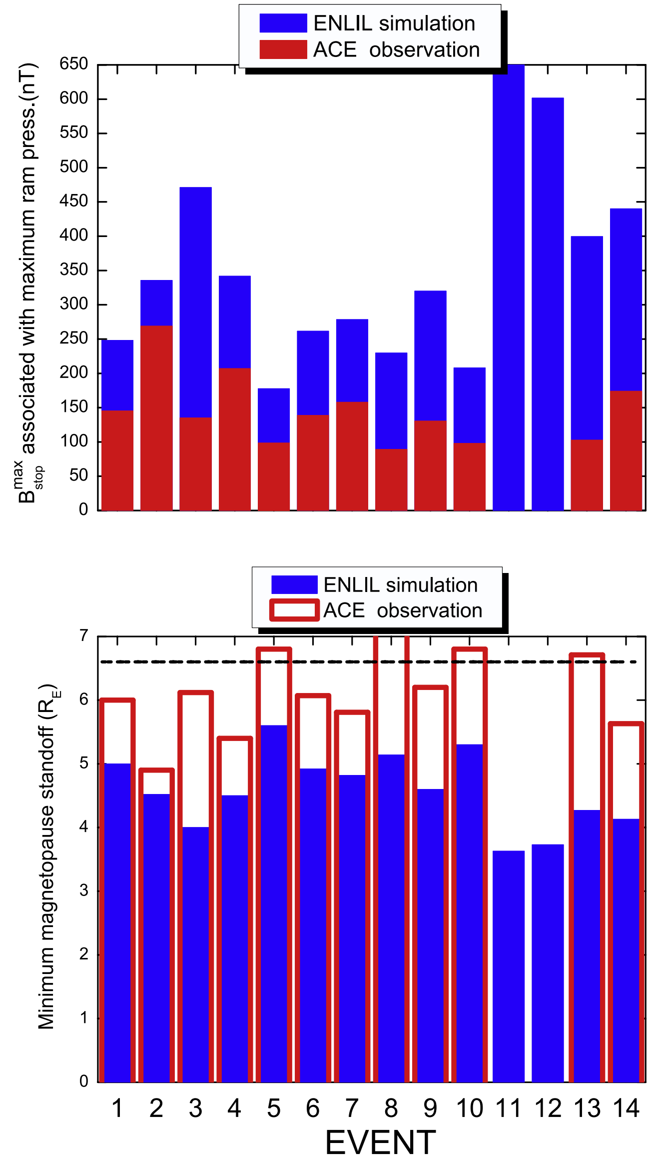

Figure 4. (top) The maximum values of the magnetic field B_{stop} (in nT) for the 14 CME events. (bottom) The minimum values of the magnetopause standoff distance corresponding to the B^{max}_{stop} shown in Figure 4 (top). Blue columns are the ENLIL calculations, and the red columns are the ACE measurements. The dashed line in Figure 4 (bottom) corresponds to the geosynchronous orbit radius 6.6 R_E.

data available for the 28 and 29 October 2003 CMEs arrival times). The current ENLIL version assumes a spherical homogeneous cloud launched in the heliosphere which gives a large momentum (dynamic pressure). The discrepancy should be smaller in the upcoming version of ENLIL with the flux rope-like structure.

[25] The same result, naturally, is reflected in the minimum magnetopause standoff distances, shown in Figure 4 (bottom). Here the horizontal dashed line represents the geosynchronous orbit distance Rgs = 6.6 R_E. Anticipating magnetopause standoff distance at or inside Rgs is especially important for the satellite operators for various reasons. We see that the model overestimates the deformation of the magnetopause for all of the 14 events we modeled. GOES satellite data analysis indicates that the magnetopause got inside the geosynchronous orbit probably only in 7 out of 14 cases. Note that the lower limits of the estimated standoff distances are shown in Figure 4 and that these correspond to the instantaneous peaks of the ICME disturbance at the magnetopause. These values probably will not be sustained for long period of time.

[26] To understand why the ENLIL cone model runs overestimate the ICME density we performed additional simulations for three events assuming the free parameter of the initial density ratio factor (df) between the CME and the ambient fast solar wind to be equal to, df = 2, instead of df = 4. The result for B_{stop} for the 13 December 2006 CME is shown in Figure 3 (top). Note that the maximum value is reduced by more than 20%. At the same time the shock arrival time is estimated to be approximately 7 hours later than in the previous case of df = 4. Similar results were obtained for two other events (17 November 2001 and 25 July 2004) with a reduction of the B_{stop} peak value by 20–25%, and delay of the estimated shock arrival time by 4–5 hours. So, df = 2 gives more realistic estimate for the ICME dynamic pressure impact on the magnetosphere in this case. At the same time, the delay of the shock arrival improves the model performance because, for df = 4 we have earlier shock arrival predictions in majority of our cases.

5. Summary

[27] We studied the performance of the ENLIL cone model in modeling the propagation of CMEs in the heliosphere. We compared the results of the simulation with the ACE satellite observations and performed metrics analysis.

[28] The results of the ENLIL cone model for 14 fast CME events are analyzed focusing on two important parameters: the arrival time of the ICME shock and the magnitude of the ICME impact on the magnetosphere. The magnitude of the ICME impact is characterized by the magnetic field magnitude needed to stop the ICME mass flow. The corresponding magnetopause standoff distance is also calculated.

[29] In this set of modeled 14 cases there are more earlier arrival predictions (9 out if 14) than late arrival predictions. The errors in the earlier arrivals are, on the average, larger than those of the late arrival predictions. The average absolute error is approximately 6 hours for the total set.

[30] We compared simulation results to two reference model results: (1) propagation of the CME shock with a constant velocity corresponding to the average velocity of all halo CMEs during 1996 – 2007, taken from the SOHO/LASCO CME catalog (850 km/s) and (2) the empirical shock arrival model (ESA) of *Gopalswamy et al.* [2005]. The ENLIL cone model performs better than the reference models for the most of the fast CME events that we studied. We conclude that physics based ENLIL cone model performs well compared to considered reference models as far as shock arrival time is concerned. It has to be noted that different CME speeds can be obtained using different cone model approaches, some of them resulting in better agreement with transit timing for particular CME.

[31] We also estimated the magnitude of the impact of CMEs on the magnetosphere by calculating the magnetic field strength required to stop the solar wind stream. The results show that the ENLIL cone model overestimates the dynamic pressure impact for all of the studied events. This result is naturally reflected in estimated minimum magnetopause standoff distances. The model predicts the pushing of the magnetopause boundary inside of the geosynchronous orbit for all of our 14 CME events, while GOES data indicates that this probably happened in half of the cases.

[32] Finally, by using ENLIL (and MHD simulation in general), we are able to predict, with less accuracy than the shock arrival times, magnetospheric parameters such as the the magnetopause standoff distance, or as done, for example, by *Toth et al.* [2007], Dst index and cross-polar cap potential. Empirical models cannot be used for these purposes.

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