Refined Modeling of Geoeffective Fast Halo CMEs During Solar Cycle 24

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Abstract The propagation of geoeffective fast halo coronal mass ejections (CMEs) from solar cycle 24 has been investigated using the European Heliospheric Forecasting Information Asset (EUHFORIA), ENLIL, Drag-Based Model (DBM) and Effective Acceleration Model (EAM) models. For an objective comparison, a unified set of a small sample of CME events with similar characteristics has been selected. The same CME kinematic parameters have been used as input in the propagation models to compare their predicted arrival times and the speed of the interplanetary (IP) shocks associated with the CMEs. The performance assessment has been based on the application of an identical set of metrics. First, the modeling of the events has been done with default input concerning the background solar wind, as would be used in operations. The obtained CME arrival forecast deviates from the observations at L1, with a general underestimation of the CME impact speed.

Plain Language Summary Coronal mass ejections (CMEs) are massive explosions of magnetized plasma hurled into the interplanetary space. The ones traveling directly toward or away from the observer’s line of sight are called halo CMEs because of their appearance as a ringlike white light feature surrounding the occcluding disk in the coronagraph instruments monitoring the Sun. Because of their course of propagation, the Earth–directed halo CMEs are more likely to strongly disturb the geomagnetic field and subsequently trigger intense geomagnetic storms. Therefore the accurate prediction of halo CMEs arrival at Earth is critically important to mitigate their hazardous effects on human technology in space and on the ground. This work attempts to assess the performance of several models for CME propagation for a selected set of fast Earth–directed halo CMEs. A refinement in the modeling input was implemented that lead to a significant improvement in the forecast for the halo CME arrivals.

1. Introduction

Coronal mass ejections (CMEs) are one of the major drivers of space weather on Earth and in the solar system in general (Bothmer & Zhukov, 2007; Schwenn, 2010; Schwenn et al., 2005; Temmer, 2021). They can cause severe damage to human technology and infrastructure, and therefore it is of paramount importance to forecast their arrival as accurately as possible. For this purpose, over the years the forecasting efforts have amounted to a plethora of CME propagation models incorporating various approaches (Riley et al., 2018). Some models employ numerical methods to solve the magnetohydrodynamic (MHD) equations, for example, ENLIL (Odstrcil et al., 2004), European Heliospheric Forecasting Information Asset (EUHFORIA; Pomoell & Poedts, 2018), the 3-D MHD simulation model H3D-MHD (Wu et al., 2007, 2011), CORona-HEliosphere (CORHEL, Mikić, 1990), and Alfvén Wave Solar Model (AWSomM, Van Der Holst et al., 2014). Other models are based...
on empirical relations between parameters measured from white-light images from coronagraphs and spacecraft measurements at L1 (Gopalswamy et al., 2001; Paouris & Mavromichalaki, 2017a) and recently on machine learning (e.g., Camporeale, 2019; J. Liu et al., 2018; H. Liu et al., 2019; Sudar et al., 2016). In addition, heliospheric imager (HI) data, as those onboard the Solar TErrestrial RElations Observatory (STEREO; Kaiser et al., 2008; Howard et al., 2008), are crucial for more accurate forecast and can be used as complementary information to any propagation model (e.g., the ELlipse Evolution model based on Heliospheric Imager (ELEvoHI, Rollett et al., 2016; Hinterreiter et al., 2021) and the Heliospheric Reconstruction and Propagation Algorithm (HeRPA, Paouris & Vourlidas, 2022)). Since HI observes the CMEs at distances from tens to hundreds of solar radii, \( R_\odot \) that is, at later times in the CME evolution, the improved prediction comes at the expense of a reduced lead time (e.g., Colaninno et al., 2013).

On average, CMEs consist of several distinct parts, which we are able to distinguish well in white-light coronagraph images, with the most pronounced structures referred to as flux ropes and shock-sheaths (Vourlidas et al., 2013). The same structures can be identified from in-situ measurements, where also additional sub-structures are detected, but it is not fully understood how these relate to the observed white-light structures (Kilpua et al., 2020; Temmer & Bothmer, 2022). Globally, the flux rope and shock-sheath halo CME parts can be approximated by two simple geometrical shapes: a cone shape coming from the original ice-cream cone model, representing the flux rope, and an ellipsoid representing the shock-sheath (Xie et al., 2004).

Halo CMEs appear as a distinct type of CMEs. Their name originates from their visible morphology in coronagraph images, where they manifest as increased brightness structures surrounding the occulting disc of coronagraph instruments. As it is the shock signature that causes the 360° brightness enhancement, halo CMEs are usually very energetic and they have their main propagation direction toward or away from the observer's line of sight. In stereoscopic images, the shock is more clearly observed as a sphere, which causes the halo effect in the projected data, as it extends further and wider than the magnetic flux rope (Kwon et al., 2015). The CME speed and width (lateral expansion) are found to be correlated, meaning that faster CMEs become halos earlier, due to their stronger expansion that compresses the plasma to a higher density, so that they appear as halos from a wider range of viewing angles (Dal Lago et al., 2003; Kwon et al., 2015).

The solar corona and the interplanetary (IP) space are both structured and dynamic, containing plasma and magnetic field of various properties which can affect several CME characteristics, including the kinematic properties and propagation direction. For example, CMEs originating close to a streamer, or coronal hole, can get strongly decelerated and deflected from its radial propagation direction (Gopalswamy et al., 2009; Gui et al., 2011; Heinemann et al., 2019; Möstl et al., 2015; Y. Wang et al., 2004; J. Wang et al., 2020). There is increased awareness that the interaction and evolutionary processes in IP space differ between the magnetic flux rope structure and shock-sheath. The modeling needs to account for all possible interactions, especially those with stream interaction regions or other CMEs, which is not an easy task. Due to such complexity, the currently available models for CME propagation have an accuracy in the arrival time prediction of about ±10 hr. However, the forecast errors have a big spread and often can exceed 20 hr (Riley et al., 2018; Vourlidas et al., 2019). There are various pitfalls in the modeling that are responsible for such inaccuracy—starting from the uncertainty of the synoptic magnetograms (Riley et al., 2014) used in the numerical schemes to extrapolate the coronal and ambient solar wind conditions, which are averaged over 27 days period and evolve from solar rotation to rotation. Then come the assumptions for the CME initial speed, cone parameters and shock front shape that are affected by projection effects in the plane-of-sky (Burkepile et al., 2004), which are especially severe for halo CMEs. Other pitfalls are the missing information about magnetic effects due to CME-CME interactions and other local inhomogeneities in the inner heliosphere (Lugaz et al., 2017). Last but not least there is a forecasters’ bias, based on different objectives in the selection of the events and the skills of the modellers (Verbeke et al., 2019, 2023). This unapparent issue can actually have large impact on the forecast accuracy and has been recognized by the International Space Science Institute as an important question to be investigated in the team Understanding Our Capabilities In Observing And Modeling CMEs (https://www.issibern.ch/teams/understandcormasseject/index.php/team-goals/).

In general, the performance of models decreases with increased solar-activity phases as CMEs more frequently disturb the IP space, and with that have a preconditioning effect that background solar wind models are not able to fully cover (Cranmer et al., 2017; Temmer et al., 2017). Especially empirical solar-wind models are not able to cope with those disturbances, but preconditioning has an important effect also for numerical models (e.g.,
The more frequent interactions occurring between CMEs and other transients during solar maxima further complicate CME predictions at target locations (Scolini, Chané, Temmer, et al., 2020; Winslow et al., 2021), requiring numerical simulations to be described in a realistic fashion.

In this study we focus on the most effective drivers of intense geomagnetic storms, namely halo CMEs. While model performance and validation is usually done on CMEs with very different characteristics, we use a more consistent, yet small set of halo CMEs, which caused geomagnetic effects during solar cycle 24. From a forecaster’s perspective, the forecast of fast halo CMEs is the biggest challenge. Knowing that a full hit is highly likely, models need to be run quickly with reliable input parameters. Here, we test the performance of the EUHFORIA model (Pomoell & Poedts, 2018), ENLIL model (Odstrcil et al., 2004), the Drag-Based Model (DBM) (Vršnak et al., 2013) and Effective Acceleration Model (EAM) (Paouris et al., 2021; Paouris & Mavromichalaki, 2017a), for a common set of halo CME events with the same input parameters and the same metrics (Verbeke et al., 2019) to compare the model predictions. It is worth noting that our work is aligned with the objectives of the recent space weather community initiatives regarding the establishment of common metrics for CME arrival times, for example, the Community Coordinated Modeling Center’s (CCMC) CME Arrival Time and Impact Working Team (https://ccmc.gsfc.nasa.gov/assessment/topics/helio-cme-arrival.php) as part of the COSPAR international Space Weather Action Teams (ISWAT) initiative on CME structure, evolution and propagation through heliosphere (https://iswat-cospar.org/h2).

The paper is organized as following: in Section 2, the data set and the CME parameters are introduced. In Section 3, a brief description of the used models is provided, while in Section 4, the modeling results for the CME shock arrival times and their speeds, referred as to impact speeds, from default and refined runs are presented and discussed in the frame of the recent advances of the community. In Section 5 the results are summarized and highlighted.

2. Data

We have selected a group of 12 halo CME events which have similar characteristics: they are Earth-directed, fast (>1,000 km/s), originating from the area around the solar disk center (±30° heliographic longitude from the solar meridian), and are geoeffective. The events corresponding to these selection criteria represent a subset of a larger database of halo CMEs from solar cycle 24 (Scolini et al., 2018). We have chosen this database to make use of the kinematics of the CMEs, which have been carefully estimated for the purposes of reconstruction of their propagation with WSA-ENLIL + Cone modeling by Scolini et al. (2018).

Table 1 shows the parameters that have been used as input to the models we test. The date and time of the CME observation at 21.5 solar radii (hereafter \(R_\odot\)) from LASCO C3 (second column) is taken from the DONKI database under https://kauai.ccmc.gsfc.nasa.gov/DONKI/: the initial CME speed, cone half-width angle and CME solar source coordinates are taken from Scolini et al. (2018): and finally, the date and time of arrival of the observed interplanetary shock (IPS), its speed and the background solar wind speed preceding the IPS, come from WIND spacecraft measurements at the Lagrange point L1.

3. Models

We investigate the propagation of the halo CME events using the numerical models ENLIL (Odstrcil et al., 2004) and EUHFORIA (Pomoell & Poedts, 2018), the analytical DBM (Vršnak et al., 2013) and the empirical EAM (Paouris et al., 2021; Paouris & Mavromichalaki, 2017a). In the following we give a short description for each of the respective models.

3.1. ENLIL and EUHFORIA

The most used model in operations for heliospheric and CME arrival predictions is ENLIL (Odstrcil et al., 2004). ENLIL is a 3D MHD heliospheric model coupled with the semi-empirical Wang-Sheeley-Arge (WSA) coronal model (Arge & Pizzo, 2000), which provides the solar wind and magnetic field conditions at the heliospheric model inner boundary. In this work, we employ ENLIL version 2.8f available through the CCMC (https://ccmc.gsfc.nasa.gov/models). The solar wind conditions at the inner boundary of the heliospheric domain, located at
Table 1

List of Halo Coronal Mass Ejection (CME) Events and Relevant Parameters

<table>
<thead>
<tr>
<th>Event</th>
<th>Date/time* at 21.5R⊙</th>
<th>(v_0) (km/s)</th>
<th>(w) (°)</th>
<th>Lon (°)</th>
<th>Lat (°)</th>
<th>Date/time at L1</th>
<th>(T_\mu) (h)</th>
<th>(V_{IPS}) (km/s)</th>
<th>(V_{SW}) (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2 June 2011/11:25</td>
<td>1,147</td>
<td>66</td>
<td>-25</td>
<td>-19</td>
<td>4 June 2011/20:00</td>
<td>57</td>
<td>450</td>
<td>350</td>
</tr>
<tr>
<td>2</td>
<td>6 September 2011/15:00</td>
<td>1,232</td>
<td>66</td>
<td>7</td>
<td>14</td>
<td>9 September 2011/10:00</td>
<td>67</td>
<td>500</td>
<td>320</td>
</tr>
<tr>
<td>3</td>
<td>19 January 2012/18:34</td>
<td>1,269</td>
<td>66</td>
<td>-22</td>
<td>32</td>
<td>22 January 2012/05:33</td>
<td>59</td>
<td>400</td>
<td>330</td>
</tr>
<tr>
<td>4</td>
<td>23 January 2012/05:20</td>
<td>2,511</td>
<td>66</td>
<td>21</td>
<td>28</td>
<td>24 January 2012/14:40</td>
<td>33</td>
<td>650</td>
<td>410</td>
</tr>
<tr>
<td>5</td>
<td>7 March 2012/01:44</td>
<td>3,146</td>
<td>66</td>
<td>-27</td>
<td>17</td>
<td>8 March 2012/10:30</td>
<td>33</td>
<td>800</td>
<td>500</td>
</tr>
<tr>
<td>6</td>
<td>10 March 2012/20:20</td>
<td>1,638</td>
<td>66</td>
<td>24</td>
<td>27</td>
<td>12 March 2012/08:29</td>
<td>36</td>
<td>520</td>
<td>400</td>
</tr>
<tr>
<td>7</td>
<td>14 June 2012/16:35</td>
<td>1,254</td>
<td>66</td>
<td>-6</td>
<td>-17</td>
<td>16 June 2012/09:03</td>
<td>40</td>
<td>410</td>
<td>300</td>
</tr>
<tr>
<td>9</td>
<td>16 February 2014/21:22</td>
<td>1,064</td>
<td>66</td>
<td>-1</td>
<td>-11</td>
<td>18 February 2014/06:06</td>
<td>33</td>
<td>450</td>
<td>390</td>
</tr>
<tr>
<td>10</td>
<td>9 September 2014/04:16</td>
<td>1,080</td>
<td>66</td>
<td>-29</td>
<td>12</td>
<td>11 September 2014/22:50</td>
<td>67</td>
<td>460</td>
<td>380</td>
</tr>
<tr>
<td>12</td>
<td>22 June 2015/21:10</td>
<td>1,573</td>
<td>66</td>
<td>8</td>
<td>12</td>
<td>24 June 2015/13:07</td>
<td>40</td>
<td>750</td>
<td>530</td>
</tr>
</tbody>
</table>

Note. Columns 1: date and time of the CME observation at 21.5R⊙ extrapolated from LASCO C3 observations, Column 2: initial CME speed, Columns 3: cone half-width angle, Columns 4–5: source region longitude and latitude in HEEQ coordinates, Column 5: Columns 6–10: observed CME shock arrival time, transit time, background solar wind speed \(V_{SW}\) and impact speed \(V_{IPS}\) at L1 by WIND spacecraft.

21.5 R⊙ are extrapolated from photospheric magnetic field synoptic maps (in this study we use GONG magnetic field data) using the WSA coronal model (Arge & Pizzo, 2000). The heliospheric model is able to provide full 3D outputs of the MHD variables (i.e., the plasma number density, velocity components and thermal pressure, and the magnetic field components) at a given time, as well as high-cadence (5- to 10-min resolution) time series of the MHD variables at notable target locations, including the Earth. We employ a standard computational domain for the heliospheric model, extending from 21.5 R⊙ (corresponding to 0.1 AU) to 2 AU in the radial direction, spanning ±60° in latitude, and ±180° in longitude. To achieve fast computing times, we use a resolution of 4° in the latitudinal and longitudinal directions.

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due to weaker background magnetic field. In ENLIL, the CME is assumed to have constant speed, and four times larger density (represented by the parameter $dcld = 4$) and the same temperature as the ambient fast solar wind. In comparison, EUHFORIA uses as default value $dcld = 2$. In terms of the cone CME model, slight differences in the implementation and initialization between ENLIL and EUHFORIA are present, which can affect the modeled CME geometry as discussed by Scolini et al. (2018) and Scolini, Chane, Pomoell, et al. (2020). Both model outputs cover time profiles of the plasma density and velocity, magnetic field and dynamic pressure for the Earth, to be compared to in-situ measurements.

### 3.2. DBM and EAM

One of the most commonly used analytical models is the DBM (Vršnak et al., 2013). It is used for predicting the Time-of-Arrival (ToA) of the CME shock and its impact speed at a certain target. The model is based on the assumption that the MHD drag in the collisionless solar wind environment adjusts the CME speed at some distance to that of the ambient solar wind (Cargill, 2004; Vršnak et al., 2010). As the CME travels through the IP medium, MHD waves are emitted resulting in a drag effect that can be described by equations analogous to the aerodynamical drag. This is supported by observations as it has been found that in relation to the solar wind, slow CMEs accelerate while fast CMEs decelerate (Gopalswamy et al., 2010; Sachdeva et al., 2015; Sheeley et al., 1999).

DBM, which uses the basic drag equation of motion as given in Vršnak et al. (2013) and applies a 2D geometry of the CME (with the leading edge as a semicircle that spans over the entire width expanding in a self-similar manner), was developed over the years. The latest (ensemble) version (Čalogović et al., 2021) is based on the 2D model that combines the DBM equation with flattening cone geometry (Sudar et al., 2022; Žic et al., 2015), describing the propagation of the CME leading edge, which does not evolve self-similarly and is currently available as ESA service for Heliospheric Weather (https://swe.ssa.esa.int/heliospheric-weather). The DBM runs have been obtained also via the ESA-SWE Services, using the model version DBEMv3 (Čalogović et al., 2021). The required input parameters basically describe the CME initial conditions at a specific distance from the Sun where a purely drag dominated kinematical CME evolution can be assumed. The parameters cover the CME width, the speed, the longitude of the propagation direction—usually estimated through the source region location—as well as an estimate of the ambient solar wind speed in which the CME propagates (see more details on the different DBM versions in Dumbović et al., 2021). The last input parameter—most important for this work as it is related to the $dcld$ value from the numerical models—is the drag parameter $\gamma$, which depends on the properties of both the CME and the ambient solar wind and should therefore be unique for each event. It was shown that a common value range $\gamma = 0.1 - 0.2 \times 10^{-7} \text{ km}^{-1}$ can be used for a large subset of CMEs and performs similarly to ENLIL in terms of accuracy of arrival times (Vršnak et al., 2013). The drag value $\gamma = 0.1 \times 10^{-7} \text{ km}^{-1}$ is recommended for fast CMEs as given in the guidelines of the model. However, recent studies have shown that this value might not be suitable (Paouris et al., 2021; Čalogović et al., 2021).

Similar to the DBM concept, the EAM is a data driven empirical model which predicts the ToA of the CME’s associated shock and the average speed within the sheath at 1 AU (Paouris et al., 2021; Paouris & Mavromichalaki, 2017a). The model is based on the assumption that the ambient solar wind interacts with the interplanetary CME (ICME) resulting in constant “effective” acceleration or deceleration. The core of the model is an empirical relation for the acceleration as a function of the initial speed of the CME. This relation is obtained from a large CME/ICME catalog of 266 events utilizing coronagraph and in-situ data (Paouris & Mavromichalaki, 2017b), covering solar cycle 23. For a given initial CME speed the empirical relation gives the effective acceleration (or deceleration). Thus it is possible to estimate the ToA of the CME or of the preceding shock, via simple kinematic equations. In our analysis, the upgraded version of EAMv3 (Paouris et al., 2021) is applied for the estimation of the ToA, as well as for the impact speed of each CME (see the event list in Table 1). For simplicity, we will refer to the model version as EAM further in the paper. EAM is not publicly available yet thus the results are obtained from the developer E.P.

### 4. Results and Discussion

Using the different models as described above, we derive forecast results for the given sample of halo CMEs. We investigate the uncertainties of the CME forecast in terms of ToA and the speed of the shock associated
with the CME (impact speed). The impact speed is important for determining the CME geoeffectiveness, since it contributes to the plasma dynamic pressure and the electric field that are exerted on the magnetosphere from the incoming solar wind. In a first step, we use default setup parameters and the same initial CME parameters (see Table 1) for all models. At this stage, all halo CMEs are treated as isolated events, meaning that only one CME is inserted in the model runs. In that respect, we note that only events no. 2, 7, and 10 are real isolated CMEs. In the next steps, we refine the model runs by varying model parameters and insert multiple CMEs into the numerical models. Note that while in ENLIL and EUHFORIA the background solar wind is calculated over the entire heliosphere from the input photospheric magnetic field information (see also Section 3.1), for DBM the background solar wind is derived from WIND in-situ plasma bulk speed measurements prior to the CME shock (see Table 1, last column). EAM is a data-driven model, and its performance was evaluated on a very large data set as mentioned in the previous section (Paouris et al., 2021; Paouris & Mavromichalaki, 2017b). As a result, it serves as a benchmark baseline for the modeling performance. It is important to note that the data set used to establish the empirical relation for the EAM model consists of CMEs from solar cycle 23, while the modeled events belong to solar cycle 24.

Throughout the paper, the model performance and forecast accuracy are based on the following metrics: mean error (ME), mean absolute error (MAE), and root mean square error (RMSE) (Paouris et al., 2021; Riley et al., 2018; Verbeke et al., 2019), which are calculated for the CME ToA and the impact speed. The standard errors of these metrics were calculated by applying a simple bootstrap method with replacement for $10^6$ runs (see e.g., Paouris et al., 2021; Paouris & Mavromichalaki, 2017b).

### 4.1. Modeling With Default Input Parameters

The results for the CME ToA prediction from the four models with default (unrefined) input are shown in Figure 1 (top panel). The colored bars along the Y axis, represent the difference dToA in the arrival time predicted for each model with respect to the observed arrival at L1 ($t = 0$, marked with the horizontal black line). There is a wide spread in the modeled ToA, with a tendency toward earlier prediction visible from the ME estimation in Table 2, representing the error statistics of the modeling results. Despite the spread, there is an overall agreement between the models in the predictions for each individual event.

Table 2

<table>
<thead>
<tr>
<th>Errors</th>
<th>EUHFORIA</th>
<th>ENLIL</th>
<th>DBM</th>
<th>EAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>dToA, h</td>
<td>ME</td>
<td>$-10.2 \pm 3.3$</td>
<td>$-7.4 \pm 4.0$</td>
<td>$-12.4 \pm 3.2$</td>
</tr>
<tr>
<td></td>
<td>MAE</td>
<td>$13.0 \pm 2.3$</td>
<td>$13.3 \pm 2.4$</td>
<td>$14.6 \pm 2.3$</td>
</tr>
<tr>
<td></td>
<td>RMSE</td>
<td>$15.3 \pm 2.2$</td>
<td>$15.6 \pm 2.2$</td>
<td>$16.7 \pm 2.3$</td>
</tr>
<tr>
<td>dV, km/s</td>
<td>ME</td>
<td>$376 \pm 54$</td>
<td>$180 \pm 40$</td>
<td>$356 \pm 40$</td>
</tr>
<tr>
<td></td>
<td>MAE</td>
<td>$376 \pm 54$</td>
<td>$180 \pm 40$</td>
<td>$356 \pm 40$</td>
</tr>
<tr>
<td></td>
<td>RMSE</td>
<td>$419 \pm 58$</td>
<td>$227 \pm 36$</td>
<td>$382 \pm 44$</td>
</tr>
</tbody>
</table>
Figure 2. Observed versus predicted impact speed from the four models in color for all events. The dashed lines represent linear fit for each model. The correlation coefficients $cc$ are given in the legend in color. The black dotted line shows the perfect match between the two speeds. DBM results correspond to runs with $\gamma = 0.1 \times 10^{-7}$ km$^{-1}$. ENLIL and EUHFORIA runs are performed with $dcld = 4$ and 2, respectively.

In conclusion, on average the models overestimate the impact speed for fast halo CMEs. The smallest error statistics is produced by the EAM model, where ME = $0.1 \pm 3.3$ hr. As seen from the standard error the EAM, ME results from the cancellation of positive and negative time differences between observation and prediction of the ToA. The largest deviations from the actual CME arrivals (ME = $-12.4 \pm 3.2$, MAE = $14.6 \pm 2.3$, RMSE = $16.7 \pm 2.3$ hr) are produced by the DBM model run with input drag parameter $\gamma = 0.1 \times 10^{-7}$ km$^{-1}$, which is the default value for fast CMEs ($V > 1,000$ km/s). The overall tendency of a too fast CME propagation implies that in the models there is insufficient drag from the ambient solar wind. In the numerical simulations with ENLIL and EUHFORIA, the drag felt by CMEs during propagation can be altered by changing the so called density enhancement factor ($dcld$), which is the ratio between the CME and the fast solar wind densities. Higher $dcld$ values indicate denser CMEs, resulting in reduced solar wind drag and therefore in faster CME propagation. As described in Section 3.2, the default input value used in the runs are $dcld = 4$ in ENLIL and $dcld = 2$ in EUHFORIA. In the next step, we will thus lower the default $dcld$ values in order to make the CMEs less dense, slowing down their propagation. For DBM the drag is lowered by increasing $\gamma$ instead of reducing $dcld$, which will be tested in the following.

4.2. Assessing Event-Based Ambient Conditions

Inspecting Figure 1, most results are consistent among the models, covering events with early forecasts (events no. 1, 2, 3, 5, 8, 10, 11) or delayed prediction (events no. 7, 9). For some predictions the models disagree (events no. 4, 6, 12), and we have no clear result, that is, they are both early and delayed (diverse). The large discrepancies between observations and modeling, using default parameters and treating CMEs as isolated events, suggest that the IP space experiences large variations from case to case. To better understand pre-conditioning effects due to the propagation of preceding single or interacting CMEs, we investigate in more detail remote and in-situ data. It has been shown by Temmer et al. (2017) that it may take 2–5 days for the IP space to recover from the propagation of a single-CME. We use the DONKI database to check the solar activity, hence, CME eruptions and high speed streams (HSS), within a time range of 4 days prior and 2 days after the respective CME eruptions. Earth-related solar wind conditions were checked from in-situ WIND measurements at Lagrange point L1 in a time window of 4 days before the detected CME arrival. In the following, we discuss the different categories (early, delayed, diverse forecast) with respect to the assumption of isolated CMEs.

4.2.1. Early Prediction

Figure 3 shows WIND measurements for event no. 11, which reveal a very complex transient arriving at L1, where the vertical magenta line marks the IP shock. Ahead of the shock, the solar wind is slow and stationary.
Behind the shock, it is very difficult to identify the different ICME regions. There are five compression intervals characterized by sudden increases of the magnetic field intensity and plasma density (panels a and c, respectively). The first one is associated with the IP shock. Behind the shock follows the sheath region highlighted in yellow. The second compression is embedded at the leading edge of a very disturbed magnetic structure (highlighted in green). We define the magnetic structure by the features in the plasma parameters, such as low density and proton temperature, respectively low plasma $\beta$ (the ratio between plasma and magnetic pressures), and by the higher magnetic field with respect to adjacent the intervals. At the trailing edge of this structure is the third compression region (highlighted in violet). The magnetic field exhibits two large rotations and two step-wise increases and gradual decreases in the magnitude indicative potentially for an interaction of two different flux ropes. The fourth compression (highlighted in violet) is associated with another local magnetic field magnitude bump, rotation in the $B_z$ component, and plasma $\beta$ below 1 in the violet box consistent with flux rope properties. From the DONKI database we can see that there were two slightly slower CME eruptions before (19 December 2014/01:12, 885 km/s, $-20^\circ$ lon, $-9^\circ$ lat in Heliocentric Earth Equatorial coordinates) and after (20 December 2014/04:09, 964 km/s, $23^\circ$ lon, $-43^\circ$ lat), which have probably interacted in the IP space with the CME discussed here and led to a deceleration. Indeed, in-situ we observe three distinct decreasing velocity profiles (panel b) with a sharp leading and slowly decreasing trailing part can be recognized in panel (b). A decreasing velocity profile results from the effect of expansion of a propagating CME. This supports further the suggested scenario that we observe a multiple CME interaction. The fifth compression (highlighted in gray) is due to a following HSS.

### 4.2.2. Delayed Prediction

The delayed prediction of event no. 9 was likely facilitated by the presence of another ICME, as shown from the in-situ measurements in Figure 4 (beige box). The preceding ICME arrived 3 days ahead on 15 February 2014, and might have strongly changed the initial characteristics of IP space. This is evident from the very large density

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**Figure 3.** WIND observations of event 11. (a) Magnetic field magnitude and components, (b) plasma velocity, (c) plasma density, (d) plasma temperature, and (e) proton plasma $\beta$. The vertical magenta line marks the IP shock, the yellow box highlights the sheath region associated with the shock, the green box—the following distorted magnetic ejecta, the violet—another magnetic structure compressed by the incoming HSS (gray box).

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**References:**

enhancement associated with it (panel c) and the very rarefied plasma left behind in the day prior the ICME arrival, despite that the trailing solar wind stream was slow, which typically has high density. There are three increases in the speed (panel b), related to the different CME regions (from left to right): first comes the IP shock at 18 February 2014/06:06 (magenta vertical line) and the sheath (yellow box), followed by the magnetic cloud in the green box. From the magnetic field we see that the flux rope is deformed and strongly compressed—the magnetic field magnitude (panel a) and the plasma parameters (panel b–d) show a sharp increase probably due to another shock (panels a–d) on 19 February 2014/03:10, coinciding with density pile-up (panel c) due to the influence of the faster ICME incoming from behind (violet box). An alternative explanation would be that the shock and the sheath of the ICME from behind had penetrated event no. 9 forming the so called shock-in-a-cloud structure (Lugaz et al., 2017). Finally, there is another shock at ~02:40 UTC on 20 February 2014 that probably belongs to a fast stream (gray box), characterized by high velocity, high temperature and low density (panels a–d), catching up and squeezing the ICMEs ahead. In the remote observations one can see strong solar activity in the days around event no. 9’s eruption that have very likely contributed to the formation of this stacked IP transient.

4.2.3. Diverse Prediction

The modeling results for the events described in the categories above are consistent—they forecast either early or delayed arrival. For the events no. 4, 6 and 12, however, the models disagree. For example, for event no. 6, EUHFORIA predicts nearly accurate ToA (~0.5 hr), ENLIL and EAM delayed (12.8 and 10.7 hr), and DBM early arrival (~3.3 hr). The impact speed predictions are also very different between models. For event no. 12—they are large positive for EUHFORIA and DBM (163 and 257 km/s), negative for EAM (~103 km/s), and ENLIL perfectly matching the observed one. Interestingly, this category of events includes one of the fastest CMEs (no. 4) in this sample. One would expect that given the extremely high initial speed 2,511 km/s (see Scolini et al., 2018), all models should predict clearly an early arrival. From the in-situ measurements for event no. 4 shown in Figure 5, we can see that a preceding ICME (which is event no. 3 in our list) have swept the IP space.
and left a rarefied background. This lower density region enabled the following after fast ICME (event no. 4) to propagate even faster, experiencing reduced drag from the background solar wind and so resulting in only 33 hr transit time. Such a fast propagation, however, is not seen in the modeling results, suggesting potential discrepancies in the solar wind representation in the models.

4.3. Refined Modeling: Changing \( dcld \) and \( \gamma \)

For forecasters in operational centers, the detailed analysis of preconditioning of IP space is a time-consuming and demanding task. The main parameter to cope for higher CME rates during increased solar activity is the drag. Changes in terms of \( dcld \) (which is the ratio between CME and background solar wind densities) in ENLIL and EUHFORIA, and \( \gamma \) (which includes also the ratio between CME and solar wind densities) in DBM relate to the background solar wind condition. The early CME arrival tendency for most of the events under study, confirms previous validation efforts reporting similar results, namely strong deceleration for fast CMEs and overestimation of the launch speed, which leads to an overestimated impact speed (Čalogović et al., 2021; Dumbović et al., 2018; Mays et al., 2015). For example, the most commonly used 3D MHD heliospheric WSA-ENLIL + Cone ensemble modeling generates \( ME = -5.8 \) hr on average, and the error increases up to \( -19.4 \) hr for fast CMEs (Mays et al., 2015). Kay et al. (2020) found that solar wind speed is important for weak/slow CMEs while solar wind density is more important for fast CMEs. Mays et al. (2015) also found that besides the CME input speed and its uncertainties, the CME density has a major effect on the CME arrival time prediction. In that respect, Scolini et al. (2018) derived better arrival times with ENLIL when lowering the density ratio to \( dcld = 2 \). Recently, Paouris et al. (2021) has shown that the underestimation of the arrival time by the DBM model is related to the underestimated drag parameter. Specifically, in a sample of 15 CMEs/ICMEs the optimal drag parameter was found with a mean value of \( \gamma = 0.33 \times 10^{-7} \) km\(^{-1}\). As a next step, we therefore assess the performance of the models by refining the model input using such recent results from the literature.

DBM uses as default value for the modeling of fast CMEs \( \gamma = 0.1 \times 10^{-7} \) km\(^{-1}\), which leads to a large underestimation of the arrival of the CMEs under consideration. It is worth noting that this recommendation was based

![Figure 5. WIND observations of event 4. (a) Magnetic field magnitude and components, (b) plasma velocity, (c) plasma density, (d) plasma temperature, and (e) proton plasma \( \beta \). The different colored boxes correspond to event 3 (in beige) and event 4 (in red).](image-url)
the best model performance resulting from the validation work with observations from the previous solar cycle 23 (Vršnak et al., 2013, 2014). Obviously, this value is too low for the set of events here, which belong to cycle 24. Therefore, we increased the drag parameter as suggested by Paouris et al. (2021). From that we found a significant improvement when using $\gamma = 0.2 \times 10^{-7}$ km$^{-1}$, that can be seen in both ToA in Figure 6 (top panel) and impact speed (bottom panel), as well as in the statistics presented in Table 3 (ME = $-3.8 \pm 3.2$ hr, MAE = $9.9 \pm 1.8$ hr, RMSE = $11.7 \pm 1.7$ hr). For $\gamma = 0.3 \times 10^{-7}$ km$^{-1}$, the statistics are slightly better in absolute terms (MAE = $8.6 \pm 2.2$ hr) and reveal an opposite trend ME = $3.3 \pm 3.2$ hr, that is, ToA is overestimated.

From the scatter plot of the impact speeds in Figure 7 (similar layout as Figure 2) and the corresponding errors in Table 3, we see that the same kind of improvement is achieved when using $\gamma = 0.2 \times 10^{-7}$ km$^{-1}$ (ME = $120 \pm 15$ km/s, MAE = $120 \pm 15$ km/s, RMSE = $131 \pm 15$ km/s). The smallest errors (ME = $24 \pm 14$ km/s, MAE = $51 \pm 6$ km/s, RMSE = $55 \pm 7$ km/s) result from $\gamma = 0.3 \times 10^{-7}$ km$^{-1}$. All events (dark blue stars in Figure 7) are distributed closely to the dotted-black line indicating perfect match between the observation and prediction, which is reflected also in the highest correlation coefficient $cc = 0.94$ for this $\gamma$ value. We did not further test values of $\gamma > 0.3 \times 10^{-7}$ km$^{-1}$, because larger drag values caused a reversed tendency of later time of arrivals as seen in Figure 6 (top panel) and underestimation of the modeled speed, for some of the events (bottom

![Figure 6. DBM comparison of dToA (top panel) and dV differences (bottom panel). The color bars show the model predictions for $\gamma = 0.1$, 0.2, and 0.3 ($\times10^{-7}$ km$^{-1}$).](image-url)
As a conclusion, using $\gamma = 0.3 \times 10^{-7}$ km$^{-1}$ for this CME data set produces the best prediction according to the used metrics in terms of both ToA and impact speed. Our tests confirm the recent validation results for DBM (Čalogović et al., 2021), where the same optimal drag parameter was found.

Previous studies have shown that ENLIL is most sensitive to changes in the initial density and velocity of the modeled CME (Falkenberg et al., 2010; Taktakishvili et al., 2010). However, there is a large spread in the range of values of the ratio between the densities of the CMEs and solar wind existing in the literature. For example, based on white light observations, the true density compression ratio at CME–associated shocks was determined to be in the range $1.3–4.6$ (Kwon & Vourlidas, 2018), while in Temmer et al. (2021) it was suggested that the ratio has to be higher ($11–6$) for distances $15–30 R_\odot$. In a case study by Susino et al. (2015), the evolution of the compression ratio of the CME–driven shock was followed up to $10 R_\odot$. It was found that the compression ratio has a profile dependent on the heliocentric distance and latitude—with maximum value $\sim 2.1$ at the center of the shock closest to the Sun at around $-20^\circ$ in latitude, decreasing to $\sim 1.5$ at the flanks and farthest away from the Sun (Susino et al., 2015). The discrepancies in these studies are probably due to different data sets (incl. different solar cycles) and different versions of the models (Falkenberg et al., 2010). In addition, while the CME geometry derivation has been largely investigated (e.g., Mays et al., 2015), the estimation of the CME density and its evolution from remote observations has not been done comprehensively until recently (Temmer & Bothmer, 2022; Temmer et al., 2021).

The effect of solar wind drag in the cases of ENLIL and EUHFORIA models was tested here by varying the $dcld$ parameter. The run results from three values of $dcld$ have been compared in Figure 8 (top panel), where the pink color range corresponds to ENLIL and the blue one to EUHFORIA. Higher value of $dcld$ indicates that the CME is more dense and it will propagate faster since it would experience less drag from the solar wind. Given the overall very fast propagation of the CMEs under study we use for EUHFORIA in consistency with ENLIL the value $dcld = 4$, in addition to $dcld = 2$, shown to be optimal for ENLIL by Scolini et al. (2018), and $dcld = 1.2$ determined for a case study using ENLIL covering multiple CME events by Werner et al. (2019).

To avoid confusion, we would like to remind the reader that in the EUHFORIA case the default $dcld$ value is 2. Not surprisingly, using $dcld = 4$ gives the largest average error from all tests in both models (see Table 4).
Exception are events no. 7 and 12, as shown in Figure 8 (top), for which input with dcld = 4 gives small ToA difference: −1.2 hr (EUHFORIA) and −0.9 hr (ENLIL), respectively. ENLIL’s prediction is largely spread with RMSE = 18.1 ± 3.1 hr and 15.5 ± 2.1 hr for the lower values dcld (1.2, 2), which is due to nearly half of the events predicted to arrive later than observed. EUHFORIA is systematically underestimating the ToA, with ME (−6.8 ± 3.3 hr, −10.2 ± 3.3 hr, −13.7 ± 3.3 hr) for dcld = 1.2, 2, 4 (in Table 4), except for events 7 and 9. On other hand, EUHFORIA’s prediction of the ToA for events no. 6, 7 and 12 is very small in comparison with the respective ENLIL forecast.

The effect of the density factor on the predicted impact speed can be seen in Figure 8 (bottom panel), where the yellow, orange and red bars represent the speed difference dV for EUHFORIA, and with light to dark green bars—for ENLIL for dcld = 1.2, 2 and 4, respectively. Both models show a predominant overestimation of the impact speed. In addition, there is a significant difference in the metrics (Table 4) between the two models—regardless of the value of the density enhancement, EUHFORIA predicts much larger impact speed than ENLIL. For example, there is one order of magnitude difference between ENLIL (ME = −28 ± 37 km/s) and EUHFORIA (ME = 243 ± 45 km/s) for the smallest (1.2) dcld factor. This discrepancy is probably to a larger degree influenced by the different default values of dcld in the two models.

The results from the various tests are summarized in Table 5. It is important to emphasize at this point, that the smallest errors in the refined modeling result from different set-up in the numerical models: for EUHFORIA, both dToA and dV are achieved with dcld = 1.2. However, for ENLIL the smallest dToA is obtained with dcld = 2, while the smallest dV comes from a modeling input with dcld = 1.2. Also, if the model performance is considered regarding either ME or MAE—the smallest errors may not belong to the same model, that is, the models’ order may be different when ranked by ME compared to MAE. For example, the ME for ENLIL is smallest with −0.1 ± 4.5 hr using dcld = 2, for DBM we derive 3.3 ± 3.2 hr with γ = 0.3 × 10⁻⁷ km⁻¹, and for EUHFORIA

<table>
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<tr>
<th>Table 4</th>
<th>Prediction Errors From EUHFORIA and ENLIL Runs With Different Values of the Density Enhancement Factor dcld and Their Standard Errors</th>
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<tbody>
<tr>
<td>Errors</td>
<td>EUHFORIA</td>
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<tr>
<td></td>
<td>dcld = 1.2</td>
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<tr>
<td>dToA, h</td>
<td>ME</td>
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<td></td>
<td>MAE</td>
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<td>RMSE</td>
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<tr>
<th>Table 5</th>
<th>Refined Model Performance for Time of Arrival and Impact Speed, Incl. Their Standard Errors.</th>
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<tr>
<td>Errors</td>
<td>Single-CME</td>
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<tr>
<td></td>
<td>EUHFORIA</td>
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<td>dToA, h</td>
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Note. The optimization in modeling with single-CME input is done with dcld = 1.2 in EUHFORIA, dcld = 2 for dToA and dcld = 1.2 for dV in ENLIL, and γ = 0.3 × 10⁻⁷ km⁻¹ in DBM. EAM results are provided here as a baseline. The errors from the multi-CME input in ENLIL and EUHFORIA is provided in the last two columns. Note, that the multi-CME metrics is calculated on the basis of 9 out of 12 CME events (see Section 4.4), while the single-CME metrics is based on all 12 events.
−6.8 ± 3.3 hr with \(dcld = 1.2\). Regarding the MAE, we derive the smallest value for DBM with 8.6 ± 2.2 hr, for EUHFORIA 11.5 ± 2.0 hr and for ENLIL 13.5 ± 2.2 hr. Similarly, the ME for the impact speed is smallest for ENLIL with −28 ± 37 km/s, for DBM 24 ± 14 km/s and for EUHFORIA (243 ± 45 km/s), while for the MAE we derive for DBM the smallest value with 51 ± 6 km/s, ENLIL (111 ± 20 km/s) and EUHFORIA (243 ± 45 km/s). Regardless of the metrics however, it is clear that the improved model performance results from the customary adjustments of the drag and \(dcld\) parameters, showing clearly the need of a more realistic representation of the background solar wind in the modeling.

Figure 9 summarizes the best model results using refined parameters and testing more recent literature findings. We note again, that EAM is excluded from the refinement because there is no drag adjustment for this model as this was part of the model development itself. EAM is therefore a statistical baseline (see results given in Section 4.1) that is presented in Figure 9.

4.4. Multi-CME Input and Modeling Results Discussion

As described in Section 4.2, there are preconditioning effects due to multiple CMEs. We further perform a comparative testing and evaluate the effect on ToA and impact speed when including more than one CME into the numerical models ENLIL and EUHFORIA (note that DBM and EAM have no such option). We implemented multi-CME input for events no. 1, 3, 4, 5, 6, 8, 9, 11, and 12. There were no CME eruptions close in time and location that could have potentially contributed to events no. 2, 7, and 10. As already described in Section 4.2, the additional CMEs that were included in the input were selected by taking into account the solar activity from DONKI database a few days before and after the time of the eruptions in our events. Results for the three exemplary events, as discussed before, are presented in detail in the following. A summary for all multi-CME events is given later.

Figure 10 shows the radial velocity (panels a and c) and plasma density (panels b and d) for event no. 11 from the ENLIL and EUHFORIA simulations at target Earth. The three time profiles from each model cover runs with single-CMEs and default values (solid light blue/red for ENLIL/EUHFORIA), single-CMEs and refined values...
In addition, vertical lines show the arrival forecast from DBM with default/refined input (cyan/green) and from EAM in yellow. For comparison, in-situ WIND measurements are given in gray and the actual CME ToA as vertical dash-dotted magenta line. This event produced the earliest arrival forecast in all models. Since, the background solar wind is rather well represented by the numerical models, a possibility to account for the large discrepancy between prediction and the observation could be the suggested interactions described in Section 4.2.1 (Figure 3).

These interactions likely decelerated event no. 11, resulting in 64 hr transit time. At the same time in the modeling runs there are no distinguishable features in the solar wind that could facilitate a slowing down of the propagation of the CME launched with high initial speed. From the different modeling setups (Figure 10), the multi-CME in the numerical models and the default DBM input results in the earliest of the predictions. Reducing the $\text{dcl}_{\text{d}}$ from 4 to 2 in ENLIL, and from 2 to 1.2 in EUHFORIA, moves the modeled CME shock closer to the actual ToA. The same effect is achieved by increasing the drag parameter $\gamma$ from $0.1 \times 10^{-7} \text{ km}^{-1}$ to $0.3 \times 10^{-7} \text{ km}^{-1}$. The dark yellow vertical line marks the arrival time prediction from EAM model. The actual arrival of the CME is marked by the vertical dash-dotted magenta line.

Figure 11 presents the results from the various model runs for event no. 9, covering the same parameters as described in Figure 10. Event no. 9 is associated with a delayed forecast (see Section 4.2.2). From this example it becomes apparent that when the numerical prediction features a late ToA, the refinement of the density ratio would delay the ToA even more. The multi-CME simulation overlaps with the single-CME run in ENLIL, and the respective runs in EUHFORIA are also not very different from each other. The refined DBM results do not provide an improvement in the forecast either, and also coincided with EAM ToA. The assessment of the ambient solar wind condition presented in Section 4.2.2 (Figure 4) revealed that the IP space has been preconditioned from a preceding CME. However, most probably the effect of this preceding CMEs was not large. The inspection of the solar wind speed in the observations (Figure 10) shows a higher speed than the one of the simulation, especially in the case of ENLIL, suggesting an inaccurate solar wind modeling. One source of such mismatch could be due to the uncertainty in the GONG synoptic magnetogram input.

Analogously to the previous examples, Figure 12 shows the outcome of the different simulation setups for event no. 4. The ToA errors for this event from the default modeling input were rather small, as given in Section 4.1.
Inserting more CMEs clearly leads to increased underestimate of ToA in both numerical models. In the ENLIL case, the ToA is in general closer to the actual arrival, and reducing $dcld$ causes a change in the forecast to a later arrival. Similar change from early to delayed arrival occurs in the case of DBM for the refined input. EAM predicts the closest ToA. Interestingly, EUHFORIA forecasts from the three different inputs (default, refined, multi-CME) still produce an early CME arrival. Further, EUHFORIA's velocity and density profiles have quite different shapes from the ones of ENLIL. The simulated background solar wind has low speed and high density in both models, quite different from the observed one (high speed and low density). This could be again, as suggested in the previous example, due to the uncertainty and discrepancy in the solar wind input at the inner boundary in both models. Other possibilities could be the preconditioning from the preceding ICME (see Section 4.2.3 and Figure 5) or a combination of the two.

A comparison between multi-CME, default single-CME and refined-drag single-CME runs for all 9 events is presented in Figure 13. We remind the reader, that only 9 out of the 12 events have multi-CME runs. Therefore, when the metrics of ToA and impact speed of the multi-CME runs is compared with the single-CME ones and discussed further in the text, only the corresponding 9 events are taken into account in the single-CMEs' error calculations (see the comment in the caption of Table 5). For the default value $dcld = 4$ in ENLIL and $dcld = 2$ in DBM.
in EUHFORIA, the multi-CME input produced an improvement in the ToA with 1.1, 0.9 and 0.3 hr for ENLIL events no. 1, 3, and 9. The derived changes, however, are small in comparison to the other events. Most probably, the additional CMEs related to event no. 1 (4 June 2011/09:52, 1,589 km/s, 16° lat, 144° lon; and 4 June 2011/23:41, 2,850 km/s, 16° lat, 153° lon) and event no. 3 (23 January 2012/05:55, 2,511 km/s, 28° lat, 21° lon) had small effect on the propagation because they start from the Sun two, respectively, four days later and originate from different source regions. In the case of event no. 9, the two prior CMEs (15 February 2014/14:54, 1,627 km/s, 17° lat, −52° lon; 7 March 2012/02:12, 3,146 km/s, 17° lat, −27° lon; 7 March 2012/03:32, 2,096 km/s, 25° lat, −26° lon; 9 March 2012/08:08, 1,229 km/s, 15° lat, 3° lon) were slow and launched from the east solar limb, causing only weak interaction effects. The largest difference between the multi- and single-CME input was obtained for event no. 6, where the ToA has improved by 10.5 hr. This event was significantly delayed in the single-CME run. Inserting in ENLIL the preceding four fast CMEs (5 March 2012/06:53, 1,627 km/s, 17° lat, −52° lon; 7 March 2012/02:12, 3,146 km/s, 17° lat, −27° lon; 7 March 2012/03:32, 2,096 km/s, 25° lat, −26° lon; 9 March 2012/08:08, 1,229 km/s, 15° lat, 3° lon) covers the preconditioning of the IP space, facilitating the faster propagation of event no. 6. However, for the rest of events no. 4, 5, 8, 11 and 12, the multi-CME runs resulted in a larger dToA error, namely, the difference in MAE increased with 3 hr with respect to the corresponding single-CME input. The largest difference was obtained for event no. 12, where the underestimation in ToA in the multi-CME input increased with 7.3 hr compared to the single-CME ToA prediction. Except for event no. 1 with slightly better dToA of 0.2 hr, EUHFORIA multi-CME input predicts early arrival, with up to 10.5 hr difference from the single-CME input for event no. 12, and MAE = 2.9 hr (all events), reiterating ENLIL’s multi-CME modeling behavior.

The effect of multi-CME input on the CME speed is much more significant, except again for events no. 1, 3 with no significant difference with respect to the single-CME input. The MAE = 423 km/s for the multi-CME input in ENLIL (Table 5), compared with MAE = 319 km/s from the respective single-CMEs with default input, has an increase of 105 km/s. All EUHFORIA multi-CME runs produced overestimated speed with MAE = 697 km/s, which gives an increase of 281 km/s compared to MAE from the single-CME runs (MAE = 416 km/s).

The ToA for the multi-CME input in comparison to the single-CME refined input for ENLIL (dcld = 2) and EUHFORIA (dcld = 1.2) showed some improvements. In ENLIL, the differences between the two inputs for events no. 3, 6 and 9 were 10.8, 24, and 7 hr, respectively, bringing the ToA closer to actual arrival in the multi-CME modeling. However, for the rest of the events, the refined single-CME prediction yields better results, in detriment of the multi-CME one (MAE = 9.7 hr). In EUHFORIA, only event no. 9 shows an improvement in
dToA with 2.5 hr in the multi-CME run, for the other events dToA increased with 6.2 hr with respect to the single-CME runs.

The decreased density factor $dcld$ leads to a reduced difference between the predicted and the observed impact speed in the refinement (see Table 5). However, in ENLIL, the prediction is spread in both ways—under to over-estimation. This leads to a decrease with 39 km/s in the discrepancy between the multi-CME speed (MAE = 423 km/s) and refined single-CME speed (MAE = 462 km/s) for ENLIL. For EUHFORIA the refined modeling yields to better impact speed prediction, where the representative MAE = 409 km/s is smaller than MAE = 697 km/s of the multi-CME runs.

We conclude that by inserting more than one CME, on average we do not derive an improved CME forecast. Keeping in mind that there is general tendency in the numerical modeling of early arrival and overestimated speed prediction, modeling input with more than one CME might worsen the forecast. On the one hand, with each additional CME more uncertainties about the CME kinematics are introduced. Also, it is still demanding for the numerical models to handle multi-CME input. The CME-CME interaction processes are not well understood and may also depend on the magnetic configuration of the CME flux ropes (see e.g., Lugaz et al., 2017). The cone models we are using here are completely lacking the magnetic structure of the CME, which is a major issue when trying to model CME-CME interaction processes. In cases where IP preconditioning is plausible, simulating multiple CMEs may be beneficial. However, a more sophisticated input would be necessary, which may not be feasible in operational settings.

5. Summary and Conclusions

In this work we have assessed how well fast halo CMEs, that is, the most geoeffective CMEs (Dumbović et al., 2015; Zhang et al., 2007), may be forecasted by using EUHFORIA, ENLIL, DBM and EAM models, by using a set of events from solar cycle 24. Halo CMEs, occurring most frequently during enhanced solar activity, are affected most by projection effects and may suffer from preconditioning effects of IP space. This makes the prediction of fast halo CMEs the biggest challenge for forecasters. Simulations of the ambient heliospheric conditions, as well as input parameters into the models, are subject to large uncertainties. Moreover, extensive multi-CME inputs to numerical models are time-consuming. The small sample population of halo CMEs from this study is limited but special, since it contains fast geoeffective halo CMEs with similar characteristics that also belong to the ascending and maximum phases of solar cycle 24. Given that the solar activity in the current cycle 25 is approaching maximum, this analysis is timely and relevant for the attempts to improve the halo CME forecast.

The predictions of CME arrival time and impact speed based on the four different models have been compared to the corresponding observations at L1. We assessed the model performances: (a) using default model parameter values with simple CME configurations, (b) using simple CME configurations with refined values by applying more sophisticated literature recommendations for the model drag parameters, (c) testing most realistic and more complex multi-CME run scenarios. We find that:

- Default model parameters give uncertainty ranges for the CME arrival time of, MAE: 13.0 ± 2.3 hr (EUHFORIA), 13.3 ± 2.4 hr (ENLIL), 14.6 ± 2.3 hr (DBM) and 9.8 ± 1.8 hr (EAM); ME: −10.2 ± 3.3 hr (EUHFORIA), −7.4 ± 4.0 hr (ENLIL), −12.4 ± 3.2 hr (DBM) and 0.1 ± 3.3 hr (EAM). There is a clear trend toward an early CME arrival prediction. Similarly, all models show an almost constant overestimation of the CME-associated shock speeds with MAE: 376 ± 54 km/s for EUHFORIA, 180 ± 40 km/s for ENLIL, 356 ± 40 km/s for DBM, and 151 ± 35 km/s for EAM; and ME—same as MAE, except for the EAM model (ME = 178 ± 22 km/s).

- Refined model input by decreasing the ratio between the densities of the CME and the ambient solar wind and increasing the drag parameter (excluding EAM since such input is not possible), delays the fast CME propagation and improves the prediction. This results in MAE: 11.5 ± 2.0 hr (EUHFORIA), 13.3 ± 2.2 (ENLIL) and 8.6 ± 2.2 hr (DBM); ME: −6.8 ± 3.3 hr (EUHFORIA), −0.1 ± 4.5 hr (ENLIL) and 3.3 ± 3.2 hr (DBM), where the refinement was done with $dcld = 1.2$ for EUHFORIA and $dcld = 2$ for ENLIL.

- Similarly, the increased solar wind drag remedied the large overestimation of the impact speed by reducing significantly the deviation between prediction and observation to: 243 ± 45 km/s (EUHFORIA), 111 ± 20 km/s (ENLIL) and 51 ± 6 km/s (DBM) for MAE, and for ME: 243 ± 45 km/s, −28 ± 37 km/s, and 24 ± 14 km/s, respectively, and $dcld = 1.2$ was used in both models EUHFORIA and ENLIL.
The advanced multi-CME input in the numerical models that would account for preconditioning effects is not always producing better forecast. Most likely interaction processes are not sufficiently covered yet, hence, uncertainties increase, which is not useful in operational settings.

None of the used models gives “perfect” forecasts. Model development, and hence, model validation, should be routinely adjusted to the specifics of the solar cycle phase.

Our findings identify the $dc/dt$ parameter (the density ratio of the CME and solar wind) in the numerical models ENLIL and EUHFORIA, and the drag parameter $D$ in DBM, as most practical parameters that may be easily changed for improving halo CME forecasts. Even though EAM model does not contain either of these parameters, the CME interaction with the background solar wind is included empirically. The inaccurate prediction by the models performed with default parameters shown in this work is probably due to variations in the state of the plasma in the heliosphere when having different phases of solar activity (isolated vs. multiple CME events, as well as changes in the background solar wind itself). Most models have been developed and validated on events that occurred during specific phases of a specific solar cycle, with the bulk of the model validation and parameters testing work done during cycle 23. It is well known that substantial differences in the physical properties of the solar wind populating the heliosphere during different solar cycles may exist (see e.g., Gopalswamy, 2006; Gopalswamy et al., 2022; Gopalswamy, Xie, et al., 2015; Gopalswamy, Yashiro, et al., 2015; Micheal et al., 2022, and references therein). Therefore, permanent assessment of the solar cycle variations, regarding in particular the background solar wind, needs to become an integral part of the forecast operations.

Furthermore, fast halo CMEs, as being one of the most hazardous space weather phenomena, are especially difficult to predict since they require extra care in the determination of their 3D geometry and properties. Therefore, their forecast can greatly benefit from multi-point observations from various vantage points in the heliosphere. A step in this direction will be achieved in the near future by the collaborative efforts of international space agencies when Vigil (ESA) and SWFO-L1 (NASA) will be placed respectively at L5 and L1, and GOES-U (NASA)—in geostationary orbit.

Data Availability Statement

The WIND spacecraft data were downloaded from the Coordinated Data Analysis Web (CDAWeb) database (NASA, GSFC, 2021). The ENLIL model was run from the public Request system of the Community Coordinated Modeling Center at Goddard Space Flight Center (CCMC NASA GSFC, 2022). The EUHFORIA (Pomoell & Poedts, 2018) and DBM (Žic et al., 2015) models were run from the Heliospheric Weather of the ESA Expert Service Centers (ESA, SSA, 2021). The empirical EAM ($v^3$) model is described in Papouris et al. (2021). All modeling results are available from Zenodo (Yordanova, 2023). All figures are produced with Matlab2021b (© 1984–2021 The MathWorks, Inc.).

References


