Operational Modeling of Heliospheric Space Weather for the Parker Solar Probe

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Abstract

The interpretation of multi-spacecraft heliospheric observations and three-dimensional reconstruction of the structured and evolving solar wind with propagating and interacting coronal mass ejections (CMEs) is a challenging task. Numerical simulations can provide global context and suggest what may and may not be observed. The Community Coordinated Modeling Center (CCMC) provides both mission science and space weather support to all heliospheric missions. Currently, this is realized by real-time simulations of the corotating and transient disturbances by the WSA-ENLIL-Cone model. We have simulated the heliospheric space weather relevant to the Parker Solar Probe (PSP) mission since 2018 September and provided numerical results to our colleagues analyzing in situ measurements published in the ApJS Special Issue. In this paper, we do not analyze PSP data, but we present recent updates in simulating the background solar wind and compare them with an existing operational model around the first PSP Perihelion, from 2018 October to 2018 December. We introduce new tools that assist in the interpretation of remote observations and in situ measurements useful for PSP and other missions, and for predicting heliospheric space weather. We also use this opportunity to evaluate recent improvements in the WSA and ADAPT-WSA coronal models that are being transitioned and considered to be transitioned, respectively, to operations. Finally, we simulate CME-like hydrodynamic ejecta with various parameters and calculated synthetic white-light images that can be used for “mid-course” correction of operational predictions.

Supporting material: animations

1. Introduction

Numerical modeling plays a critical role in efforts to understand the connection between solar eruptive phenomena and their impacts in the near-Earth space environment and in interplanetary space. Interpretation of remote observations and in situ measurements and reconstruction of three-dimensional (3D) structured and evolving solar wind with propagating and interacting coronal mass ejections (CMEs) is a challenging task. Numerical simulations can provide global context and suggest what may and may not be observed, and thus, they can provide modeling support to that effort. Modeling the origin of CMEs is still in the research phase, and it is not expected that real events can be routinely simulated in the near future. Therefore, we have developed the WSA-ENLIL-Cone modeling system, which uses remote observations of the photospheric magnetic field and white-light signatures of CMEs in coronagraphs to construct boundary conditions that drive the 3D numerical magnetohydrodynamic (MHD) code ENLIL to simulate global structure of the solar wind and transient disturbances in the inner and mid heliosphere. This “hybrid” modeling system enables the simulation of virtually any observed CME event as it propagates and interacts with the evolving background solar wind. This system ignores specifics of the magnetic eruption process; it takes the observed resulting structure and launches a hydrodynamic ejecta into the heliospheric computational domain to routinely predict heliospheric space weather, event-by-event, and much faster than real time. Its robust version has been implemented within the run-on-request service to heliospheric space weather community at NASA Community Coordinated Modeling Center (CCMC). Its operational version is used daily by forecasters at the NOAA/Solar and Space Weather Prediction Center (SWPC; Pizzo et al. 2011), UK MetOffice, and Korean Space Weather Center (KSWC). NASA/CCMC also provides both mission science and space weather support to NASA heliospheric missions.

The Parker Solar Probe (PSP) was launched on 2018 August 12 with a primary science goal to determine the structure and dynamics of the Sun’s coronal magnetic field, understand how the solar corona and wind are heated and accelerated, and determine what processes accelerate energetic particles (Fox et al. 2016). Thanks to the highly eccentric orbits of PSP, which will reach the minimum perihelion distance below 10 solar radii (R☉) from the Sun’s center, this mission will provide unprecedented in situ measurements and remote observations. Such data will also be important for the validation and sophistication of numerical space weather models. The global solar wind structure during the first PSP perihelion was simulated with numerical MHD codes by Xiong et al. (2004), Riley et al. (2019), and van der Holst et al. (2019). These simulations assumed steady solar wind and did not consider transients. Other work on global modeling includes MHD turbulence (Chhiber et al. 2019) and
solar wind reconstruction technique (Owens et al. 2019). We have simulated the heliospheric space weather relevant to the PSP mission since 2018 September, with the evolving background and with operationally fitted CME parameters, and presented the first results at the Fall AGU meeting in 2018.

We contributed to analyses of the in situ measurements published in the ApJS Special Issue on PSP. Allen et al. (2020) analyzed stream interaction regions (SIRs) observed by PSP for the first time inside of Mercury’s orbit, from 2018 September to 2019 January. During this time, several recurring SIRs were also seen at 1 au by both ACE and STEREO-A and these associations were supported by our simulations, which allowed to contextualize the inner heliospheric conditions. Cohen et al. (2020) detailed the first PSP observations of energetic particles associated with SIRs during the first two orbits, from 2018 October to 2019 March. The WSA-ENLIL-Cone simulations were used as a guide in associating the energetic particle data available near 1 au with those previously seen on PSP that were associated with coronated solar wind structures. Schwadron et al. (2020) investigated energetic particles observed by PSP from 2019 April 18 through 20 when the Sun released multiple CMEs, three of which propagated relatively near PSP, and the PSP was close to being magnetically connected to spacecraft near Earth. We simulated the propagation of CMEs through the inner heliosphere and identified their shocks and IMF connectivity. Szabo et al. (2020) investigated details of the heliospheric current sheet (HCS) measured by the PSP and compared with various model predictions, including those from our model.

In this paper, we do not analyze PSP data, but we present recent updates in heliospheric space weather simulations by the WSA-ENLIL-Cone modeling system and compare results with those provided by the current operational model during the PSP’s first solar flyby, from 2018 October to 2018 December. We present details on our modeling system and demonstrate how the current version, together with new useful visualization tools can be used for operational predictions at PSP and for interpretation of remote observations and in situ measurements conducted by PSP. We realize heliospheric simulations with different WSA inputs and with different Cone model-free parameters to explore the small-scale density fluctuations in the solar wind, track weak CME events, identify the HCS crossings, and compare the white-light synthetic images. We also use this opportunity to evaluate recent improvements in the WSA and ADAPT-WSA coronal models that are being transitioned and considered to be transitioned, respectively, to operations. Finally, we simulate CME-like hydrodynamic ejecta with various parameters and calculated synthetic white-light images that can be used for “mid-course” correction of operational predictions.

2. Heliospheric Modeling System

Our heliospheric modeling system is based on the numerical 3D MHD code ENLIL that uses: (1) the output from the Wang–Sheeley–Arge (WSA) model, which uses the photospheric magnetic field observations, and (2) geometric and kinematic parameters of the CMEs, which are fitted from the coronagraph CME observations. These data are used to calculate the time-dependent boundary conditions at 0.1 au (21.5 Rs), the inner boundary of the heliospheric computational domain used by ENLIL.

2.1. WSA Model

The WSA model (Arge & Pizzo 2000; Arge et al. 2003, 2004) is based on the coupling of the potential field source surface and Schatten current sheet models and on the use of an empirical relationship between the solar wind radial velocity and magnetic field expansion factor, and the distance of a solar wind source region from the nearest coronal hole boundary (Arge et al. 2004). The WSA model requires a map of the photospheric magnetic flux at its inner boundary condition. This can be a synoptic map constructed from full-disk magnetograph images acquired over the course of a solar rotation, or the Air Force Data Assimilative Photospheric Flux Transport (ADAPT) maps may be used to construct a pseudo-synchronous map (see ADAPT description below).

The WSA-2.2 model has been routinely used at CCMC for Runs-on-Request computations and at CCMC and SWPC for operational space weather predictions. This model utilizes photospheric synoptic maps based on data obtained by the Global Oscillation Network Group (GONG) Program, which uses a six-station network of magnetographs located around the Earth to obtain nearly continuous observations of the Sun. GONG produces a number of synoptic magnetic flux maps. For operational applications, the following three magnetic field products:

1. Standard QuickReduce Magnetogram Synoptic Maps (filename prefix mrgbq, our label “GONGb”),
2. Janus QuickReduce Magnetogram Synoptic Maps (filename prefix mrboq, our label “GONG”),
3. and Zero-point Corrected QuickReduce Synoptic Map Data (filename prefix mrzqs, label “GONGz”)

are available in near real time. For research applications, the full-calibration magnetic field product:

1. Network-Merged Daily Magnetogram (filename prefix mrrbi, backlog 111 days, our label “GONGi”)

is available with a 6-month delay. The GONG maps used in this study were the zero-point-corrected (mrzqs) maps, so are described as GONGz.

The WSA 4.5 model is a significant upgrade to WSA 2.2. A full description of the new WSA 4.5 code will be provided by C. N. Arge (2020, in preparation), but we provide here a very brief summary of the major changes. WSA 4.5 is capable of ingesting and running multi-realization input maps, such as those from ADAPT. It runs much more quickly, as the field-line tracing itself is now performed using the much more reliable and robust Runge–Kutta–Fehlberg method (RKF45). Finally, all of the PERL and IDL scripts in WSA 2.2 have been converted to Python. The input photospheric field maps used in this study are comprised of either the hourly GONGz maps or the ADAPT maps having a 2 hr cadence. While the same GONG full-disk input magnetograms are used to generate both the GONGz synoptic maps and the ADAPT photospheric field maps, the procedures for generating them are very different, and therefore, the two should, for all practical purposes, be considered like different observatories.

The ADAPT model incorporates photospheric magnetic flux transport (based on Worden & Harvey 2000) with rigorous data

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6 https://gong2.nso.edu/archive/patch.pl?menutype=f
assimilation (Arge et al. 2010, 2011, 2013; Hickmann et al. 2015) to produce improved maps of the global photospheric magnetic field. Like standard synoptic maps, they are produced by combining a series of full-disk magnetograms over the course of a Carrington rotation. However, ADAPT maps are generated by incorporating known flux transport mechanisms (differential rotation, along with supergranular and meridional flows) and with the ensemble least-squares data assimilation method to smoothly incorporate new full-disk magnetograms into the map. Data beyond 70° from disk center of the magnetograms are not assimilated into the maps since the measurements near the limb are less accurate. The ADAPT model estimates the polar fields using flux transport from supergranulation and meridional flows. The poles in the GONGz synoptic maps, however, are either directly incorporated into each new map from the individual magnetograms, or filled using extrapolation methods. ADAPT maps can be produced using input data from a number of magnetogram sources; throughout this paper, when we refer to ADAPT maps, we mean those produced using GONG full-disk magnetograms.

Table 1 lists four cases of the WSA inputs used in this paper. These cases use the same photospheric observations but differ by their processing, by the WSA model version, and by the cadence of the WSA maps. Note that the ADAPT model currently produces 12 realizations to account for the uncertainties in the supergranulation flows, “R000”–“R011” and thus there are 12 different WSA maps at the same time. Further note that the WSA-2.2 and WSA-4.5 maps have 2.5° and 2° angular spacing, respectively. The latter is an adjustment to the 2° angular spacing used by ENLIL to avoid latitudinal interpolation of the boundary values.

2.2. Cone Model

Assuming a constant angular width of CMEs observed in coronagraphs, Cone models (Zhao et al. 2002; Xie et al. 2004, 2006) enable fitting of the latitude, longitude, width, speed, and time of coronal structures launched into the heliosphere. These “classical” Cone models use single-perspective observations of halo- and partial-halo CMEs provided by the Solar and Heliospheric Observatory (SOHO) spacecraft at L1 point. The Large Angle and Spectrometric Coronagraph (LASCO) C2 and C3 coronagraphs are imaging the white light from 1.6 to 6 Rs and from 3.7 to 30 Rs, respectively. The C2 and C3 observations are used for fitting the geometric and kinematic CME parameters to the inner boundary of the heliospheric computational domain at 21.5 Rs.

The STEREO spacecraft provides multi-perspective observations with the Sun–Earth Connection Coronal and Heliospheric Investigation (SECCHI) COR2 coronagraph imaging the visible light from 2 to 15 Rs. This enables fitting by the more realistic elliptical cone (Michalek et al. 2007; Zhao 2008) or flux-rope-like structure (Krall & Cyr 2006; Themisien et al. 2009). The CME parameters can be also derived using triangulation techniques (Pizzo & Biesecker 2004). Various studies have shown that the Eruptive Flux Rope (EFR) model (e.g., Xie et al. 2009) and Graduated Cylindrical Shell (GCS) model (Themisien et al. 2009) based on STEREO A/B and SOHO observations provide a 3D measurement of CME size, propagation direction, and speed, free of the projection effect.

Multi-spacecraft observations, if available, significantly improve the determination of the geometric and kinematic CME parameters. At SWPC, Millward et al. (2013) developed the CME Analysis Tool (CAT), a new 3D graphical user interface analysis system that seeks to reduce inaccuracies by analyzing a CME using all three coronagraph images taken concurrently by SOHO and two STEREO spacecraft, which provide additional viewing locations well away from the Sun–Earth line. The user fits the CME by adjusting the 3D position of a teardrop shape in all available coronagraph views. A linear fit to the height-time measurements is used to estimate the CME speed and time at a height of 21.5 Rs (ENLIL inner boundary); although, the leading edge of the CMEs is often only possible to trace out to 15 Rs or less in an operational environment. CAT is the operational software system in routine use at the SWPC as the primary means to determine CME parameters for input into the WS-ENLIL-Cone model. It is also available in the IDL SolarSoft library community. CCMC developed the Stereoscopic CME Analysis Tool (StereoCAT) for multi-spacecraft CME measurements.8 The tool is similar to the SWPC-CAT; however, StereoCAT does not attempt to fit the geometric shape of the CME but instead triangulates the same feature visible in two coronagraph fields of view. By default, the speed and time at 21.5 solar radii is determined with a “linear fit” to two height-time measurements but there is an advanced “frame-series” mode option to compute second order fits of a sequence of height-time measurements.

In near real time, the CME parameters are derived using beacon coronagraph observations from the SOHO and STEREO spacecraft and a geometric triangulation algorithm such as the SWPC-CAT or StereoCAT. The measurements are an approximation of the true 3D speed and width of the CMEs at 21.5 Rs (ENLIL inner boundary). Often, the measurements are inferred from just a few data images, and some CMEs may be missed due to beacon data gaps. Real-time CME parameters and simulation graphical outputs are publicly available from the CCMC Space Weather Database Of Notifications, Knowledge, Information (DONKI) database.9 For a comparison of the accuracy of CME measurements from different CME catalogs, see Richardson et al. (2015).

Table 2 lists geometric and kinematic parameters of CMEs in the simulated period derived from beacon coronagraph images. These parameters were determined using the SWPC-CAT tool and archived in the DONKI database. Nearly all of these CMEs

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7 https://ccmc.gsfc.nasa.gov/swpc_cat_web/
8 https://ccmc.gsfc.nasa.gov/analysis/stereo/
9 https://kauai.ccmc.gsfc.nasa.gov/DONKI/
were faint events, did not have a clearly defined leading edge, and were, therefore, difficult to measure.

Although Cone models offer no information about important magnetic structure, they provide observationally based input that enables simple, event-by-event launching of hydrodynamic ejecta into the heliospheric computational domain. The numerical simulation then provides a global context of transient disturbances within the corotating structured solar wind. This serves as a practical solution until better near-Sun observations and more sophisticated CME models become available for operational predictions.

### 2.3. Heliospheric Model

The heliospheric code ENLIL (Sumerian god of wind) uses the ideal 3D magnetohydrodynamic (MHD) description of fully ionized plasma with two additional equations used for tracking the IMF polarity (Odstrcil & Pizzo 1999) and CME extent (Odstrcil et al. 2004, 2005). The ratio of specific heats, \( \gamma = 1.5 \) crudely reflects nonideal processes in the solar wind (Totten et al. 1995). By using this value, we were able to reproduce the temperature decrease; however, compression at the CME-driven shocks leads to higher values than the maximum value of four for ideal fully ionized plasma the maximum density compression is \((\gamma + 1)/(\gamma - 1)\). Therefore, we have incorporated the volumetric heating into the MHD model, which allows us to keep \( \gamma = 5/3 \) and provide the radial decrease of temperature as \(1/r\).

Numerical solutions of the MHD equations require knowledge of eight quantities at the inner boundary: mass density, mean temperature, three components of velocity, and three components of the magnetic field. ENLIL uses values of the radial solar wind and interplanetary magnetic field components provided by the WSA coronal model and calculates the density and temperature assuming constant momentum flux and pressure at the inner boundary at 21.5 Rs. The azimuthal magnetic field \( B_\varphi \) is determined by \( B_\varphi = B_\varphi \sin(\theta) V_{rot}/V_r \), where \( V_{rot} \) is the velocity of the source surface corresponding to the 27.2753 day rotation period of the Sun. The meridional magnetic field and the meridional and azimuthal flow velocities are assumed to be zero. An assumption of the constant momentum flux is used to derive the mass density, and the temperature is chosen to assure thermal balance on the source surface, the inner heliospheric boundary at 21.5 Rs.

Solved simultaneously are two additional continuity equations used to trace the injected CME material and the magnetic field polarity. The IMF in interplanetary space is frozen in the solar wind plasma, and the IMF polarity is passively advected by solar wind flow. The tracking of the IMF polarity by marker quantity, \( B_p \), is thus the same as the tracking of injected mass by marker quantity, \( D_p \), the only difference being that a different set of markers is traced in each case.

A monopolar IMF is imposed throughout the computational domain. It would appear to be more realistic to model the IMF with opposing polarities in the northern and southern hemispheres, separated by the HCS. However, the HCS is very thin, around 10,000 km at Earth orbit, and the mesh resolution needed to resolve such a structure is currently impractical. In the interplanetary regime, the HCS itself is a relatively passive structure, precisely because it is so thin, and its differential mass and momentum content is very small. Moreover, because the magnetic force tensor is symmetric with respect to polarity, little is lost on a large scale in treating the field as monopolar (Pizzo 1982; Odstrcil & Pizzo 1999). We have adopted this technique for time-dependent problems by solving an additional continuity equation for the quantity \( B_p \) Odstrcil et al. (2005). The quantity \( B_p \) is positive and negative for assumed positive (away from the Sun) and negative (toward the Sun) IMF polarities, respectively. Thus, the IMF is solved as a monopolar field, but its vector components \((B_x, B_y, B_z)\) are multiplied by the sign of \( B_p \) to obtain the correct IMF polarity for the analysis and visualization of results.

Originally, we have used the Flux-Corrected-Transport (FCT) schemes but an alternative Total-Variation-Diminishing Lax–Friedrichs (TVDLF) scheme was adopted due to its relative simplicity, speed, and robustness based on comparative numerical testing (Toth & Odstrcil 1996). The TVDLF scheme, which should be more precisely referenced as the Russianov MUSCL scheme with Hancock predictor is a cell-centered scheme, and it is used with the diffusive treatment of the magnetic field (Dedner et al. 2002). Parallelization of numerical computations is achieved by domain decomposition technique.

In this study, we use the “medium-resolution” grid, which is the spherical grid of \( 512 \times 60 \times 180 \) \((r, \theta, \varphi)\) and the simulation range is \(0.1 \) to \(2.1\) au in \(r, -90^\circ\) to \(+90^\circ\) in \(\theta\), and \(0^\circ\) to \(360^\circ\) in \(\varphi\). The numerical solution can be simultaneously realized on multiple grids for the same heliospheric domains but with a different number of transients. Typically, we use just two grids, one for computing the background solar wind and the other for computing the same background wind together with all CME-like transients. Further, temporal profiles at planetary and spacecraft positions can be also stored at nearby latitudinal positions, one and two grid spacing below and above the planetary and spacecraft positions.

We use a sequence of WSA maps, either with a 24 or 1 hr cadence. Numerical heliospheric computation proceeds with a
much smaller timestep (to meet the stability condition of explicit numerical schemes) and boundary values at each numerical step are interpolated from adjacent WSA maps assuming corotations onto the boundary grid used by ENLIL. As mentioned earlier, WSA-4.5 uses the same 2° spacing as ENLIL by default, and this eliminates the latitudinal interpolation (as is needed when the WSA-2.2 version with 2.5° default resolution is used). The evolving heliospheric background is created by using a sequence of WSA maps with corotated linear interpolation from nearby maps at the each numerical timestep.

Ambient solar wind model-free parameters include the fast, slow, and mean stream radial magnetic field, number density, temperature, and radial velocity, the magnetic field scaling factor (default of four for GONG inputs), the fraction of alpha particles, total pressure balance at the inner boundary, and exponential in the $N/V^2$ constant condition. These parameters are selected by comparing the model results with observations at multiple spacecraft over the GONG time period (2006 onward). The default ENLIL version and solar wind model-free parameters differ between the different implementations at NOAA SWPC and CCMC, but both anticipate upgrading to WSA-4.5, ENLIL 2.9f, and using ambient parameters $a/b$ or $a/b$ in the near future. Table 3 lists these differences. The original $a/b$ and $a/b$ parameters stem from early calibration runs that were realized for a limited period given by availability of GONG data. The $a/b$ parameters provide the best match of mean values over the 11 yr long solar activity cycle; however, during solar minimum, it provides too high values of the solar wind density. The $a/b$ parameters are better during solar minimum and they are used in this study. In research applications, it might be helpful to tune the free-model parameters to actual conditions and try their alternative specifications.

ENLIL uses geometric and kinematic CME parameters and calculates the time-dependent boundary assuming spherical hydrodynamic ejecta with homogeneous velocity, density, and temperature, which is launched at the inner boundary of the heliospheric computational domain at 21.5 Rs. The location, width, and velocity correspond to the Cone model parameters derived from coronagraph observations. We assume, as the model-free parameters, that the cloud has a uniform velocity (corresponding to the fitted CME speed), the density is four times larger than the mean density in the fast stream, and the temperature is equal to the mean temperature in the fast stream. Thus, the hydrodynamic cloud has four times larger pressure than the reference fast wind. The plasma cloud has a uniform velocity corresponding to the fitted CME speed. Further, we have assumed the cloud’s density (temperature) to be four times larger than (equal to) the mean values in the “typical” fast stream with the following parameters at 0.1 au: density $N = 200$ cm$^{-3}$, temperature, $T = 1$ MK, and radial velocity $V_r = 700$ km s$^{-1}$. Thus, the plasma cloud has about four times larger pressure than the ambient fast wind. This specification is used in the operational heliospheric space weather predictions. In Section 7, we use alternative specifications of the hydrodynamic ejecta with larger density enhancement, with ellipsoidal shape, and with the initial CME speed not slower than the background solar wind speed.

### 3. Predicting Global Solar Wind Structures

We have simulated corotating and transient heliospheric disturbances for the PSP since its launch on 2018 August 12. In this paper, we focus on a three-month-long period from 2018 October to 2018 December that involves the first PSP flyby around the Sun. We use outputs from four WSA coronal models (see Table 1) and geometric and kinematic CME parameters that were operationally fitted at CCMC and archived in the DONKI catalog (see Table 2). In this Section, we use inputs from the operational WSA-2.2 model with 24 hr cadence maps and basic default model-free parameters for the CME Cone. Figure 1 shows coronagraph observations of the 2018-11-01 CME event, which, as will be presented in Section 7, we predict to be observed by PSP in white-light. This CME was faint and, therefore, difficult to measure using the beacon data.

Figure 2 shows the time-dependent boundary values at 0.1 au (21.5 Rs) calculated from the GONGz-WSA2.2 maps with 24 hr cadence (Case 1 in Table 1) on 2018 November 2T07:31. At this time, the 2018-11-01 CME (Event 4 in Table 2) passes through the inner boundary at its maximum circular extent of 38°. Animation shows all simulated CMEs as they pass through the inner heliospheric boundary in evolving solar wind. This visualization displays values of the radial velocity, number density, mean temperature, and magnetic field components that drive numerical heliospheric simulations by ENLIL. Note that the meridional and azimuthal velocities are set to zero as well as the meridional magnetic field. It can be seen that the 2018-11-01 CME speed (220 km s$^{-1}$) is well below the surrounding values of the background solar wind (around 330 km s$^{-1}$). This situation might be incorrect though; there are no direct measurements at 21.5 Rs, and the background solar wind and the CME speeds are determined by using different observations and different methods.

In Section 7, we use alternative specifications of CME-like ejecta with the ellipsoidal (instead of spherical) shape and with the initial speed not slower than the background solar wind speed. The ellipsoidal shape has the major radius as the spherical shape and the minor radius is half of this width. Yurchyshyn et al. (2009) found that the overwhelming majority of CMEs are elongated in the direction of the axial field of post-eruption arcades and that there is a slight preference for the CMEs to rotate toward the solar equator and HCS (59% of the cases). In our simulated period, the HCS is basically flat, and we used zero tilt for all ellipsoidal ejecta.

Figure 3 shows heliospheric disturbances predicted at the PSP on 2018 November 2T18. The following spacecraft abbreviations are used: BEP = BepiColombo, HAY = Hayabusha2, KEP = Kepler, PSP = Parker Solar Probe, SPI = Spitzer, STA = STERO-A, and STB = STERO-B. This visualization provides a global context, detail view, and predicted values at
the spacecraft. The animation shows that the PSP increases its orbital speed as it approaches the Sun and gets about the corotating speed. Originally, at larger heliocentric distances, the corotating solar wind structures pass the PSP from behind but as the PSP increases its orbital speed during its solar flyby, the PSP is basically immersed in the same stream. This effect has been also observed by Riley et al. (2019) in their numerical simulations using a single coronal map as input.

Note that numerical heliospheric simulations do not have the same accuracy for all longitudes around the Sun. The most accurate (within the model’s limitations) is a segment with longitudes close to the Sun–Earth direction (central meridian) since the magnetograms are observed only by ground-based or near-Earth instruments. The accuracy of the heliospheric predictions decreases as the solar wind structures corotate to further longitudes without observations to track evolving conditions. If a
Figure 3. Predicted heliospheric disturbances on 2018 November 2T18. Global (a) and detail (b) views of the solar wind velocity (color scale) are shown at ecliptic together with the predicted values at the PSP position (c). A CME is outlined by the black contour and the HCS is shown by the white line. IMF lines passing through Earth, STEREO-A, and PSP are shown by the black–white zebra lines. Negative (positive) polarity is indicated by the blue (red) color at the region boundaries (a) and (b) and by the color-shaded plot background (c). Planetary and spacecraft positions are indicated by small spheres and boxes, respectively, with abbreviations given in the text. The combined FOV of the WISPR is shown by solid magenta lines (the region of the photosphere facing Earth line, so that the area of the photospheric magnetic map facing toward the spacecraft at this time is based on measurements from several days earlier. STEREO-A on 2018 November 1 is 103° eastward from the Sun–Earth line, so the region of the photosphere facing STEREO-A is 257° from central meridian as seen at Earth and the photospheric magnetic flux has not been observed, on average, for 14.9 days. As a result, this region of the model can be less reliable.

(An animation of this figure is available.)

4. Fluctuations in Evolving Background Solar Wind

Heliospheric simulation of the evolving background solar wind involves many small-scale “kinks” and “blobs” that are best seen as sudden shifts of the HCS position and as small-scale density structures. These features are introduced by using a sequence of the WSA maps that were independently calculated from separate magnetograms. We were hoping to increase the heliospheric prediction accuracy by using coronal maps from the latest version of the WSA model, WSA-4.5. First, this model uses finer computation of the coronal magnetic field and improved velocity formula to better reflect solar wind sources from nearby coronal holes. Further, while the radial magnetic field and radial solar wind velocity are provided at 21.5 Rs as before, the angular grid spacing is 2° now instead of the previously used 2.5°. This eliminates latitudinal interpolation performed by ENLIL for its heliospheric grid with an angular spacing of 2°, and thus, “numerical diffusion” in latitude is reduced. Finally, due to increased computational speed, the WSA-4.5 coronal maps can be provided with a cadence of 1 hr. This should reduce kinks and blobs in numerical heliospheric simulation, best visible in the HCS position, introduced by using a sequence of the WSA coronal maps as time-dependent boundary conditions driving the background solar wind.

Figure 5 compares boundary conditions at the helio-equator as a function of time calculated by ENLIL from the WSA-2.2 maps with a cadence of 24 hr (left panel) and the WSA 4.5 maps with
These conditions correspond to Case 1 and 3, respectively, in Table 1. Note that the solar wind density is a derived quantity calculated from the solar wind radial velocity assuming the constant momentum outflow at the inner boundary, i.e., \( N(\theta, \varphi) = N_0 V_0^2 / V(\theta, \varphi)^2 \), where \( N_0 \) and \( V_0 \) are scaling factors derived from the WSA-ENLIL calibration runs. This means that variation in the density has twice larger amplitude than in the radial velocity provided by the WSA model. Figure 6 compares heliospheric simulations realized with those two boundary conditions; using the WSA-4.5 maps with 24 hr cadence (left panel) and with 1 hr cadence (right panel). It can be seen that using high-cadence WSA-4.5 maps does not reduce but enhances small-scale density fluctuations, and these fluctuations do not dissipate but propagate through the whole computational heliospheric domain. See also the corresponding animation in the electronic version of the article.
Cranmer et al. (2017) reviewed our present-day understanding of the origins of ambient solar wind streams. Fast streams are known to be connected to the central region of large coronal holes, which are funnel-like regions of open field lines. Slow streams, however, appear to come from a wide range of sources, including streamers, pseudo-streamers, coronal loops, active regions, and coronal hole boundaries. DeForest et al. (2018) found that the outer corona is highly non-stationary with radially compact structures on multiple size scales. Di Matteo et al. (2019) identified quasi-periodic density structures with timescales ranging from a few minutes to a couple of hours in the slow solar wind streams observed by Helios spacecraft close to the Sun (<0.6 au). Vial & Vourlidas (2015) found that periodic density structures occur near coronal streamers with a periodicity of 90 minutes, and their acceleration and expansion through COR2 is self-similar.

Fluctuations of the solar wind parameters are observed, but they are not related to our simulations because they come from processes in the corona and not from changes in the photospheric magnetic field. The evolving solar wind in the heliosphere is driven by a sequence of WSA maps that were independently calculated from the individual synoptic magnetograms, and therefore, structures “jump” from one map to another. This is best visible in positions of the HCS. ADAPT photospheric maps smoothly assimilate new magnetograph observations, and thus, such jumps should be reduced. Therefore, the WSA with the ADAPT model should provide more consistent and more accurate surface map from which to model. However, there are a number of processes that can affect the surface flux that are not included in either traditional synoptic maps or flux transport models (e.g., new flux emergence on the far side of the Sun). Additionally, a number of choices are made in the construction and handling of the surface maps that may have a significant effect on coronal magnetic field models (e.g., the ADAPT maps are constructed such that the map has little

Figure 6 compares numerical simulations realized using the WSA-2.2 maps with 24h cadence and the WSA-4.5 maps with 2h cadence without and with the ADAPT processing of the GONG observations. Both simulations provide about the same magnetic field strength at L1 and STEREO-A (not shown here); however, the magnetic field topology is predicted differently and this causes differences in the prediction of the solar wind velocity. Predictions at L1 with the ADAPT processing are similar to those presented in Figure 4, but predictions at STEREO-A are significantly worse. The radial solar wind velocity is predicted up to 200 km s\(^{-1}\) faster than the observed values in October 18–22, November 9–22, and December 15–24 periods.

The poorer performance of the ADAPT-WSA predictions during these time periods is surprising. As explained above, the solar wind directed toward Earth generally originates on field lines connected to well-observed regions of the photosphere, while the magnetic field lines in the area of STEREO-A originate in areas of the photosphere that have on average not been observed for 14.9 days. In theory, the ADAPT-WSA predictions for STEREO-A should be better than those based on GONG synoptic maps, because the ADAPT model takes into account several processes that transport magnetic flux over the surface of the Sun and, therefore, should provide a more accurate surface map from which to model. However, there are a number of processes that can affect the surface flux that are not included in either traditional synoptic maps or flux transport models (e.g., new flux emergence on the far side of the Sun). Additionally, a number of choices are made in the construction and handling of the surface maps that may have a significant effect on coronal magnetic field models (e.g., the ADAPT maps are constructed such that the map has little...
or no net flux), and these can sometimes result in time periods where the GONGz-WSA model will perform better.

An example of such a case can be seen in Figure 8, which compares the magnetic connectivity of the STEREO-A satellite based on GONGz-WSA model and the ADAPT-WSA model for 2018 November 10. The white plus signs indicate the path of the satellite over the course of a Carrington rotation projected onto the outer boundary of the WSA model, and the black lines illustrate the footprint location of the magnetic field line connected to the satellite. The colored areas show the locations of coronal holes in the model, with the color scale indicating the speed of solar wind originating from that point. From this, it can be seen that the STEREO-A satellite in the GONGz-WSA model is connected to a number of small, low-latitude, southern coronal holes between November 6 and 9 and then near the edge of the northern polar coronal hole for the next several days. In the ADAPT map, the low-latitude southern coronal holes are not seen, and the northern polar coronal hole extends farther south; here, the satellite connects to points deeper in the northern coronal hole, resulting in higher wind speed predictions.

An increase in the ADAPT ensemble velocity spread is typically because of different current sheet crossing times between the realizations, that is, when the current sheet is at a notably north–south alignment. In addition, an increased variance within the ensemble is observed for periods where the current sheet is very close to the ecliptic. Most of the differences within the ensemble are driven by the flux distribution at the poles and greatly influence the current sheet topology. The poles are of great interest for 2018. The Helioseismic and Magnetic Imager (HMI) aboard the Solar Dynamics Observatory spacecraft estimate for the south pole has been decreasing (or flat) for the past two years; however, the ADAPT/GONG has been increasing. Understanding the source of the polar differences between HMI and ADAPT/GONG global magnetic maps warrants further study.

5. Detecting the HCS

The HCS, the largest coherent structure in the heliosphere, is a wavy surface separating two hemispheres with the opposite magnetic polarity. The HCS, as a transition between outward- and inward- directed polarities, is also known as the sector boundary, and it is important for the propagation of galactic cosmic rays (GCRs) and solar energetic particles (SEPs). The HCS topology reflects the global structure of the heliosphere, and thus, it is often used for evaluation of the prediction accuracy of heliospheric space weather models. Winterhalter et al. (1994) used high-resolution magnetic field and plasma data and found that the magnetic field reverses direction in a very narrow layer (3000–10,000 km), which is embedded in a region about 20–30 times wider than that characterized by an enhanced plasma density and depressed magnetic field strength. The thinner layer is the HCS, and the thicker layer is called the heliospheric plasma sheet (HPS). Typical values for the angular extent of the HCS and HPS in the ecliptic plane at 1 au are given as 0.001°–0.004° and 0.02°–0.12°, respectively. This is much thinner than the angular spacing of 2° used in our “medium-resolution” spherical grid. Numerical simulations typically require few computational cells to cross the HCS, and the magnetic field strength decreases down to zero. A decrease of the magnetic field pressure is balanced by an increase of the thermal pressure. This may require more than 4–6 computational cells; i.e., such structures may be more than 8°–12° broad. The synodic rotation of 27,2753 days means that 1 day corresponds to about 13.2°; i.e., there would be almost one-day-long periods of structures that differ from the real background values. This would artificially modify the predicted values near
HCS, and it may even distort the propagation of transient disturbances (Odstrcil et al. 1996). Therefore, ENLIL uses an efficient approach in which the HCS topology is traced (Pizzo 1982; Odstrcil & Pizzo 1999) with the $B_p$ quantity as given in Section 2.3.

Figure 9 illustrates why it is difficult to predict the crossing of the HCS. Values at the ecliptic plane (Figure 9(a)) suggest that the $PSP$ is clearly in the positive sector, far away from the HCS. However, visualizations at the meridional and radial slices (Figures 9(b) and (c)), passing through the $PSP$, show that the HCS has a very low inclination to the ecliptic, which complicates the reliable prediction of the HCS crossing. This Figure and animation, available in the electronic version of the article, show that it is not possible to detect the HCS crossings from using only the ecliptic plot (as is commonly used) and that a 3D topology needs to be considered.

Figure 10 shows the magnetic field sectors together with the tracing quantity $B_p$ at near-Earth, $STEREO-A$, and $PSP$ as a function of time. Note that the $B_p$ quantity at the inner boundary at 0.1 au has been normalized (by $1/r^2$) values of +1 or −1, for positive or negative polarity, respectively, and it becomes variable at larger distances due to compression and rarefaction processes in the solar wind streams. Nevertheless, heliospheric surface with $B_p = 0$ always indicates the HCS crossing. Temporal profiles in Figure 10 are shown at three spacecraft positions together with values at latitudes by 2° and 4° away from those positions. The larger spread of $B_p$ in nearby computational cells indicates lower accuracy in predicting the
Figure 9. Simulated heliospheric disturbances on 2018 October 27T00 shown on three slices passing through PSP (a)–(c) and as the temporal profile at PSP (d). Negative (positive) polarity is indicated by the blue (red) color at the region boundaries (a)–(c) and by the color-shaded plot background (d). On slices, the radial solar wind velocity (color scale) is shown with a CME (outlined by the black contour) and HCS (white line), and the positions of the planets and spacecraft are indicated as in Figure 3. IMF lines passing through Earth, STEREO-A, and PSP are shown by the black–white zebra lines. On the temporal profile, the light-green (yellow) shading displays the radial velocity at ±2° (±4°) above and below the spacecraft position. The animation begins at 2018 October 1T00:02 and ends at 2018 December 31T23:01. The realtime duration of the video is 88 s. (An animation of this figure is available.)

Figure 10. Magnetic field sectors and inaccuracy in identifying the HCS crossing at Earth, STEREO-A, and PSP (from top to bottom). The blue and red shading correspond to negative (toward the Sun) and positive (away from the Sun) magnetic field polarity, respectively. Magnetic field polarity tracer (Bp) at spacecraft is shown by black lines. The light-green (yellow) shading displays Bp values at ±2° (±4°) above and below the spacecraft position.
HCS crossing at respective spacecraft (shown as a boundary between the red and blue shading). Table 4 lists the HCS crossings that were automatically identified at PSP during its first solar flyby from 2018 October to 2018 December. The HCS crossing at latitudes by 2° away from the PSP positions are also given to indicate accuracy in these identifications. The prediction accuracy decreases with the heliospheric distance, and it is also lower for larger longitudinal separation from the Sun–Earth line (see Section 3), and these values are also given in the Table.

6. Tracking Weak CME Disturbances

In our heliospheric simulations, we use the CME parameters that were operationally fitted using the beacon coronagraph data (see Section 2.2). All observed CMEs (or streamer blowouts) were weak events (see Table 2), and their fitted initial speed at 21.5 Rs was below or slightly above the background solar wind speed calculated from the WSA coronal maps. Tracking such weak CMEs is a challenging task because there is no significant difference in the speeds, and weak dynamic interaction in the heliosphere leads only to a small distortion of the background solar wind. This is even more challenging if small-scale “blobs” are present in simulations with high-cadence WSA maps (see Figure 6).

We have developed a multi-grid technique to better identify transient disturbances by solving various scenarios simultaneously. In this paper, we use two identical numerical grids and the same numerical timestep to separately simulate the background solar wind and the background solar wind with all CMEs. This allows us to subtract the background solar wind solution and track contributions from the CME-driven disturbances while still allowing the CMEs to interact during propagation. This approach has been successfully applied in extracting parameters of interplanetary shocks for modeling SEPs and identifying the crossing of the IMF line connected to the observed CME-driven shocks (Luhmann et al. 2007, 2017), but we found it useful in tracking weak CMEs too.

Figure 11 illustrates how propagation of the 2018-11-01 CME (Event 4 in Table 2) and the CME-driven disturbances can be tracked. This CME propagates slower than the background and dynamically interacts with a background solar wind by piling up density at its trailing part (red shading) and by generating rarefaction at its leading part (blue shading). Note that CMEs propagating faster than the background cause an opposite effect; they generate compression pressure waves/shocks at the leading part and rarefaction waves at the trailing part. The CME ejecta is tracked by solving another equation (Section 2), and its extension is approximately outlined by a black contour (shown at 10% of the initial value at 0.1 au scaled by 1/r²). Such visualization helps to reliably identify simulated CME-driven disturbances even in more complex scenarios and determine whether the CME-driven shock intersects the IMF line connected to the observer. We have applied this technique to SEP events associated with the CME-driven shocks during the second PSP solar flyby (Schwadron et al. 2020).

7. Synthetic White-light Imaging

A simulated distribution of the solar wind density is used to generate synthetic images of the total and polarized white-light brightness as they might be remotely observed by heliospheric imagers. These images can assist in the interpretation of remote heliospheric observations of white light scattered on the density structures (Odstrcil et al. 2005; Odstrcil & Pizzo 2009; Howard et al. 2013), and they can be also used for “mid-course” correction of heliospheric space weather predictions. We take line-of-sight (LOS) integrals (Hundhausen 1993) through the 3D density distribution provided by the heliospheric MHD model. In this paper, we produce synthetic images of the total brightness within the angular sector ±60° away from the equatorial plane and for elongation angles from 6° to 90° in the Sun with 1 hr cadence, which allows us to construct running difference images with an “overlapping” difference of 2 hr, i.e., we subtract Image 0 from Image 2, Image 1 from Image 3, etc. This capability was developed for the heliospheric imagers HI-2 aboard the twin STEREO spacecraft, but we have generalized it for imagers at recently launched PSP and for imagers at the upcoming Solar Orbiter and PUNCH spacecraft.

The Wide-field Imager for Solar PRobe (WISPR) aboard PSP consists of two detectors, WISPR-I (inner) and WISPR-O (outer) with 40° and 58° field of views (FOVs) and with central positions nominally directed by 33.5° and 79°, respectively, away from the Sun. The total coverage of these two detectors is, therefore, between 13.5° and 108° (Vourlidas et al. 2016). The FOVs are not centered at ecliptic or equatorial plane due to spacecraft roll during solar flybys, and this direction and roll will differ from flyby to flyby. In our synthetic white-light images, we will use the nominal values of the FOV directions and mean value of the rolls of −8.7° and −2.8° for the WISPR-I and WISPR-O, respectively. Note that the roll of the second detector differs from the first one to account for the image distortion at larger elongations in WISPR-O. Hess et al. (2020) shows an example of the relative positions of the FOVs of each detector. Nistico et al. (2019) briefly discussed some of the challenges to consider when attempting to observe physical features in a spacecraft moving as quickly as PSP, as the varying radial distance as well as the changing perspective will require extra steps to accurately reconstruct structures and determine their kinematics. Liewer et al. (2019) used synthetic white-light images to visualize some of these effects and found that sequences of images can help identify coronal density features that will be

| No. | Crossing Time at PSP | Crossing Time at 2° above PSP | Crossing Time at 2° below PSP | Distance from Sun (au) | Longitude from Sun–Earth (°) | Polarity Before/After |
|-----|----------------------|-------------------------------|-------------------------------|------------------------|----------------------------|-----------------------|
| 1   | 2018-10-10T06:42:16  | 2018-10-11T05:36:35           | 2018-10-09T16:32:14           | 0.643                  | −13.044                    | +/−                   |
| 2   | 2018-10-11T15:41:35  | 2018-10-17T00:36:42           | 2018-10-22T12:19:45           | 0.516                  | −8.033                     | +/−                   |
| 3   | 2018-11-04T08:28:09  | 2018-11-05T21:16:17           | 2018-10-22T14:12:27           | 0.185                  | 7.144                      | +/−                   |
| 4   | 2018-11-09T13:33:12  | 2018-11-07T23:26:43           | 2018-10-23T11:22:14           | 0.201                  | 153.749                    | −/+                   |
| 5   | 2018-11-23T12:50:03  | 2018-11-24T05:06:41           | 2018-11-03T20:47:24           | 0.491                  | −146.303                   | +/−                   |
| 6   | 2018-12-09T05:08:25  | 2018-12-08T04:40:01           | 2018-11-17T16:59:23           | 0.712                  | −139.590                   | −/+                   |
| 7   | 2018-12-23T05:30:20  | 2018-12-23T22:55:43           | 2018-11-23T12:48:14           | 0.838                  | −141.648                   | +/−                   |
and as a
observed CMEs were weak events. Figure 12 shows the simulated
this has been a challenge in the simulated period because all
used for tracking the CMEs as they propagate through and interact
synthetic white-light is incomplete. Instead of producing images
domain blocks some lines of sight, and the calculation of the
circular segment in images
90°
during the
This means that if the
mentioned earlier, we calculate the white-light images in a segment
range value of 6°
computational boundary is seen at the elongation of 37.1°
moves closer to the Sun. When the
PSP
flies
the minimum heliocentric distance during the first Perihelion, the
corputational boundary is seen at the elongation of 37.1°. As
mentioned earlier, we calculate the white-light images in a segment
with the fixed elongation range from 6° to 90°. The minimum
range value of 6° is reached when the
PSP is at 0.428 au (92.1 Rs). This means that if the
PSP is at a heliocentric distance smaller than
0.428 au (92.1 Rs), then the inner boundary of the computational
domain blocks some lines of sight, and the calculation of the
synthetic white-light is incomplete. Instead of producing images
with a variable elongation range, to ensure unobstructed view
during the
PSP flyby, we produce them with the fixed range, 6°–
90° and mask out truncated regions. This masking is seen as a
circular segment in images (moving up and down in animations)
and as a “hill” in J-maps.

As mentioned earlier, the synthetic white-light images can be
used for tracking the CMEs as they propagate through and interact
with the structured solar wind in the inner heliosphere. However,
this has been a challenge in the simulated period because all
observed CMEs were weak events. Figure 12 shows the simulated
solar wind density together with the synthetic white-light image
just after the launch of the 2018-11-01 CME (Event 4 in Table 2).
This CME was fitted with the initial speed of 220 km s⁻¹ at 21.5
Rs, which is well below the background solar wind speed of
330 km s⁻¹ calculated from the WSA maps at that time. Therefore,
a rarefaction wave is observed at the leading edge and the
compression is at the trailing edge in the form of a bright, concave
feature that is also visible both in LASCO and WISPR
observations (Hess et al. 2020). The most prominent feature is the
compression region on the trailing edge while the rarefaction at
the leading edge is barely seen. This might lead to the false
conclusion that the CME has a much smaller radial extent.

It is difficult to track weak CMEs because they only weakly
disturb the background solar wind. Another challenge is that the
CME white-light signatures are weaker when they propagates farther
away from the Thompson surface (around which the
white-light scatters the most efficiently). In such circumstances,
density fluctuations (see Section 4) can complicate the identification
and tracking of CMEs as these, basically ad hoc density structures,
may show up with comparable white-light intensities if favorable for
Thompson scattering. This is true not only for displaying images in absolute values but for displaying their running differences too. And, displaying the initial (or base) difference (commonly used for coronagraph observations) cannot be used in displaying heliospheric disturbances because CMEs expand and much longer time periods are needed during which, however, the background structures corotate and evolve. Therefore, we have developed a novel “ambient-difference” approach to track weak CMEs in which we: (1) run two heliospheric simulations at the same time, one with and the other without

![Figure 11](image-url)
transient disturbances; (2) calculate synthetic white-light images for both simulations; and (3) display the white-light images as a difference from the ambient state.

Figure 13 compares two J-maps (elongation of white-light structures as a function of time) displayed by two techniques. The left panel shows the absolute value, and the right panel
shows the difference between simulations with and without transients. Note that: (1) we used the density enhancement six-times larger (instead of four) to differentiate it from the stream structure and (2) we had to clip the brightness (to 80% of the maximum value) to make the 2018-11-01 CME (Event 4 in Table 2) signatures visible at larger distances. However, these signatures are more visible in the ambient-difference visualization; there is no need to clip the brightness, and the 2018-10-29 CME (Event 3 in Table 2) becomes visible too.

The DONKI database entries for the CMEs notes that the CMEs were faint, did not have a clearly defined leading edge, and were, therefore, difficult to measure (see also Figure 1). This database uses a linear fit to obtain the CME speed at 21.5 Rs (ENLIL inner boundary), but there are no details from which heights the CME speeds were derived. If the CME is still

Table 5
Alternative Initialization of CME-like Disturbances

| Case | Shape     | Density | Speed       | Label   |
|------|-----------|---------|-------------|---------|
| a    | Spherical | 6x      | Fitted CME  | d6v0    |
| b    | Spherical | 6x      | Ambient wind| d6va    |
| c    | Ellipsoidal | 6x      | Fitted CME  | e6v0    |
| d    | Ellipsoidal | 6x      | Ambient wind| e6va    |

Figure 14. Synthetic white-light images of four heliospheric disturbances seen from PSP on 2018 November 2T18:00. The ambient difference of total brightness (gray scale) is shown together with the WISPR mean FOVs (dashed magenta lines) seen from PSP on 2018 November 2T18:00. The top (bottom) row shows results with simulated spherical (elliptical) ejecta and the left (right) column shows results with the initial CME speed as fitted from observations (clipped to the background solar wind value).
accelerating and the 2nd order fit to the height-time measurements is used, the CME speed will be faster at 21.5 Rs. The operationally fitted CMEs in the DONKI database also assume that the ejecta has a spherical shape.

Since we are not completely confident in the model initialization, we computed alternative scenarios that differ in the shape and the initial speed of the hydrodynamic ejecta at 21.5 Rs given in Table 5. We use the original (operationally fitted) CME speed and the alternative CME speed equal to the background solar wind. Further, we use the spherical shape (as in operational predictions) and ellipsoidal shape of the hydrodynamic ejecta (see Section 2.2). Thus, we simulate the same CME events but with four parametric variations.

Figure 14 shows the appearance of four disturbances, as specified in Table 5, in the white-light. Note that if the CME is launched with the speed below the background solar wind speed, a rarefaction (compression) is generated at its leading (trailing) part. Note further that, in all simulated cases, the resulting heliospheric disturbance spreads over large heliocentric distances and its white-light signature can be seen across the half of the combined WISPR FOV. The 2018-11-01 CME (Event 4 in Table 2) has an angular width of 38°, and it is launched with a speed of 220 km s⁻¹ (the initial CME speed extrapolated from the fitted coronagraph observations below 21.5 Rs) or 330 km s⁻¹ (adjusted to values derived from the WSA model). This means that the values can be different when different extrapolations (linear versus second order) of the CME speed and different solar wind speed adjustment are used at the inner boundary. The hydrodynamic ejecta have a spatial width of 14.26 Rs, and they take 12.43 and 8.35 hr, respectively, to fully pass through the inner boundary into the heliospheric computational domain. At these times, the leading edge of disturbance reaches the heliocentric distance of 35.76 Rs in both cases. The PSP is at 0.23 au (49.4 Rs), and the CME white-light signature stretches up to the elongation of 38°.

Synthetic white-light images are shown on 2018 November 2T18, which is by 17 hr later since the CME was launched at 21.5 Rs. Our four scenarios are distinct and this can be used for “mid-course” correction of operational predictions of heliospheric CME disturbances, especially for stronger and more visible events. Comparison with near real-time observations by heliospheric imagers then would suggest which particular scenario should be used for predictions.

8. Conclusions

We have simulated heliospheric space weather relevant to the PSP mission since 2018 September. We provided a global context of the corotating structured solar wind with transient heliospheric disturbances and contributed to the analysis of the PSP in situ measurements during the first and second solar flyby published in the ApJS Special Issue (Allen et al. 2020; Cohen et al. 2020; Schwadron et al. 2020; Szabo et al. 2020). In this paper, we did not analyze PSP data but provided details on the updated WSA-ENLIL-Cone modeling system (Section 2) and simulated the background solar wind and all observed CMEs during the first PSP solar flyby, from 2018 October to 2018 December (Sections 3–7). We introduced new tools that assist in the interpretation of remote observations and in situ measurements useful for PSP and other missions, and for predicting heliospheric space weather. We also used this opportunity to evaluate recent improvements in the WSA and ADAPT-WSA models and present alternative scenarios for launching slow-speed CMEs into the heliospheric computational domain.

We took advantage of the ENLIL’s computational speed and predicted the global solar wind structure and transient heliospheric disturbances using various inputs from the WSA and Cone models (Section 3). The computational speed is achieved by: (1) avoiding costly computations of the solar corona and magnetic eruptions (which are still not suitable for operational predictions); (2) avoiding computations over polar regions (which are important for coronal models but not for heliospheric predictions at near-ecliptic planets and spacecraft); and (3) avoiding high-resolution grids for proper computations of the HCSs by tracing the magnetic field polarity. This has enabled us to use the Linux workstation with the (older) 16-core AMD Opteron 6380 processor and finish the 3-month long heliospheric simulations (on two computational grids 512 x 60 x 180 from 0.1 to 2.1 au) within 28–30 hr.

Our predictions sometimes match but sometimes do not match observations. It is challenging to predict the solar wind streams if the spacecraft is close to a flat streamer belt. The new WSA-4.5 model provides, but not always, slightly better results than the previous WSA-2.2 model. It is also challenging to track weak CMEs that occurred in late 2018.

Numerical heliospheric simulations of the evolving background solar wind involve many small-scale “kinks” and “blobs” that are best seen as sudden shifts of the HCS position and as small-scale density structures, respectively (Section 4). These basically ad hoc structures complicate tracking weak CMEs in the solar wind (Section 6) and in the white-light images (Section 7). Using the high-cadence WSA-4.5 maps leads to more frequent blobs with slightly smaller sizes. As given in Section 4, small-scale density blobs are observed, but they originate by different mechanisms. Nevertheless, we think that our “unwanted” blobs might be used for tracking the corotating heliospheric streamer belt in J-maps.

ENLIL heliospheric simulations predict the HCS topology as a thin structure without magnetic reconnection (Section 5). This is achieved by computing the heliospheric magnetic field as monopolar and solving an additional equation for tracing the polarity. This approach avoids artifacts associated with magnetic reconnections at HCS and enables reliable identification of the HCS topology. It is challenging to predict the HCS crossing when the spacecraft trajectory is similar to the HCS tilt. We developed a new tool that helps to evaluate the accuracy of such predictions by recording and displaying values at the latitudes that are nearby spacecraft positions. We used different WSA models but got very similar HCS crossings at L1, STEREO-A, and PSP. We were hoping that using the ADAPT processing would help in predicting the HCS crossings, but we got inconsistent results beyond the Sun (Section 5). More work is needed to improve our ability to make objective choices between models constructed from different photospheric maps and using different coronal model parameters, both for the purposes of forecasting and for scientific studies. This and other models would also benefit from having multi-spacecraft observations of the photospheric magnetic field.

The WSA-ENLIL-Cone modeling system can routinely simulate all observed CMEs, event-by-event, and much faster than real time (Section 2). This system has no need for vector magnetograms around the Sun, and the CME signatures in
coronagraphs can be fitted for all longitudes around the Sun especially when the multi-perspective observations (SOHO, STEREO-A, upcoming Solar Orbiter) are available. On the other hand, launching the hydrodynamic ejecta at 21.5 Rs prevents us from predicting the impact of CMEs with embedded magnetic structures. We can simulate the propagation of magnetic spheromaks, but near real-time remote observations do not allow for the specification of their initial parameters. During the first PSP solar flyby, within our simulated 3-month long period, there were only nine weak CMEs observed, and they do not impact our results on global stream structure, evolving background, and detecting the HCS.

Tracking weak CMEs was a challenging task because there is no significant difference between the CME and solar wind speeds, and weak dynamic interaction in the heliosphere leads only to small compression of the solar wind (Section 6). In this paper, we used multi-grid approach and simulated the solar wind stream structure with and without CMEs. This allowed us to subtract the background wind solution and track contributions from CME-driven disturbances while still allowing the CMEs to interact during propagation. This approach enables reliable tracking of CME propagation in the heliosphere especially if CMEs are weak and comparable to small-scale density blobs or if CMEs propagate in complex solar wind stream structures.

A simulated distribution of the solar wind density was used to generate synthetic images of the total white-light brightness, as they might be remotely observed by the WISPR imagers (Section 7). We use results from the multi-grid simulations and produced white-light images as the difference between heliospheric simulations with and without transients to enhance the visibility of weak transient heliospheric disturbances. The 2018 November 1 CME can be seen in synthetic white-light images within the WISPR FOV. This CME was fitted with the initial speed of 220 km s\(^{-1}\) at 21.5 Rs, which is well below the background solar wind speed of 330 km s\(^{-1}\) calculated from the WSA maps at that time. Therefore, a rarefaction wave is observed at the leading edge, and the compression is at the trailing edge in the form of a bright concave structure. This feature stems from a large difference in the speeds at the inner heliospheric boundary that were determined differently by the WSA model (and adjusted for heliospheric computations of the expanding solar wind) and by the operational fitting of the CME speeds (using linear extrapolation from coronagraph signatures at low heights). Since we were not completely confident in the model initialization, we computed alternative scenarios that differ in the shape and initial speed of the hydrodynamic ejecta at 21.5 Rs. Our four scenarios are distinct, and this can be used for “mid-course” correction of operational predictions of heliospheric CME disturbances, especially for stronger and more visible events.

Improvements in the operational initialization of the heliospheric simulations can be achieved by parametric studies using science-quality data for a large number of events to suggest which type of the Cone model initialization would be more appropriate. As solar activity increases during the PSP mission, we should be able to observe more powerful CME events featuring larger initial speeds and also CME-driven shocks. Then it would be possible to evaluate the initialization of CME-like disturbance by hydrodynamic ejecta and magnetic spheromaks. A coordinated collaborative effort is needed for a deeper understanding of heliospheric space weather, validation of numerical codes, and for improving the predictive ability.

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Geometric and kinematic CME parameters were obtained from the NASA/CCMC DONKI catalog. These parameters were fitted using the coronagraph observations at SOHO and STEREO-A spacecraft.

Planetary and spacecraft positions are from NASA/GSFC Helioweb and NASA/JPL Horizons websites.

In situ measurements at L1 and STEREO-A in situ were obtained from the NASA/GSFC COHOweb website.

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