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3D pressure-corrected ballistic extrapolation of solar wind speed in the inner heliosphere

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Abstract—Solar wind parameters at different locations in the inner heliosphere can be estimated using various solar wind extrapolation methods. The simple ballistic method extrapolates solar wind parameters from the point of measurement to a chosen heliospheric position by assuming that major solar wind structures are persistent and arrive relatively unaltered to the target position. The method considers the rotation period of the Sun while assuming a constant solar wind speed during radial propagation. We improve the simple ballistic model by considering the interaction between the slow and the fast solar wind with a pressure correction during the propagation. Instead of extrapolating from the position of a single spacecraft, we apply this pressure-corrected ballistic method to 2D speed maps of the solar source surface available from solar coronal models to determine the solar wind speed in the inner heliosphere in 3D, between latitudes of $\pm 50^\circ$. We also take into account the effects of the solar differential rotation in our model. Our method is simple and fast, and it can be applied to different source surface datasets. The results of our model are validated with in situ data from the ACE spacecraft. We find that the pressure-corrected ballistic method can give accurate predictions of the solar wind in 3D.

Keywords: Solar Wind / Heliosphere / 3D / Pressure-correction

1 Introduction

Solar wind parameters, such as the velocity, density, temperature, and pressure, are important factors that shape the space environment within the heliosphere. By analysing these parameters, we can gain a deeper understanding of the complex processes occurring near the Sun, in the heliosphere, and of the interaction between the solar wind and bodies in the solar system. Variations of solar wind properties exert strong influence on the magnetospheres of solar system bodies, for instance, on Mercury (Kabin et al., 2000), on Venus (Vech et al., 2015), and on comets (Timar et al., 2017, 2019), and mediate the so-called space weather effects between the Sun and Earth (Kecskeméty et al., 2006; Pulkkinen, 2007; Facskó et al., 2008; Gopalswamy et al., 2008; Facskó et al., 2009, 2010; Kovács et al., 2014; Vörös et al., 2014; Facskó et al., 2016; Tsurutani et al., 2020; Zhang et al., 2022). The characteristics of the solar wind are usually measured by spacecraft at specific locations, for example, in the vicinity of Earth, or by probes traveling to or orbiting various other solar system bodies.

To determine the solar wind parameters in any other heliospheric locations, we have to rely on models that estimate the properties of the solar wind using different extrapolation methods.

The simple ballistic method extrapolates solar wind parameters from the point of the measurement to a chosen heliospheric position, for example, to the position of planetary bodies or other space probes. It calculates the arrival of solar wind packets at the target position assuming a constant solar wind speed during radial propagation while it also takes into account the average rotation period of the Sun for tangential extrapolation (Opitz et al., 2009). The lasso model (Dósa et al., 2018) improves the ballistic method by reconstructing the magnetic connectivity between the target and the solar source. The one-dimensional magnetohydrodynamic (1D MHD) models, such as the Michigan Solar Wind Model (mSWiM) (Zieger & Hansen, 2008; Zieger et al., 2009) or the Tao (Tao et al., 2005) model propagate solar wind radially with a 1D MHD method, while using the solar rotation for the longitudinal extrapolation the same way as in the ballistic propagation. The MSWIM2D model (Keebler et al., 2022) two-dimensionally extrapolates the solar parameters from one astronomical unit (AU) to 75 AU. These methods use solar parameters measured by spacecraft at various

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solar distances as input data and extrapolate them inwards or outwards. There are also methods that take in situ measurements from various spacecraft with the purpose to reconstruct the Parker spiral backwards to the solar corona. For example, [Biondo et al. \(2021\)](#) used a solar wind back-mapping technique on in situ measurements made by spacecraft located at 1 AU to reconstruct the Parker spiral back to 0.1 AU. There are also methods that reconstruct the local Parker spiral, for example, [Koban et al. \(2023\)](#) used a multispacecraft method to reconstruct the Parker spiral at 1 AU in three-dimensions (3D).

To be able to model the solar wind in 3D, extrapolating from a single measurement point is not enough. We need to know the solar wind properties on a surface, preferably a complete sphere where the Sun is in the centre. The solar magnetic field is measured by several ground-based solar telescopes and solar telescope systems, such as the Wilcox Solar Observatory ([Scherrer et al., 1977](#)), the Synoptic Optical Long-term Investigations of the Sun (SOLIS) instruments ([Keller et al., 2003](#)), or the Global Oscillation Network Group (GONG) which consists of six identical telescopes around the world, allowing to make 24-hour-a-day observations of the Sun ([Harvey et al., 1988](#)). Instruments onboard spacecraft also produce magnetograms, such as the Michelson Doppler Imager (MDI) instrument ([Scherrer et al., 1995](#)) of the Solar and Heliospheric Observatory (SOHO) spacecraft until 2011, its successor, the Helioseismic and Magnetic Imager (HMI) instrument ([Scherrer et al., 2012](#)) on the Solar Dynamics Observatory (SDO), or the Polarimetric and Helioseismic Imager (PHI) instrument ([Solanki et al., 2020](#)) on the Solar Orbiter. These instruments provide synoptic magnetograms, that offer a complete view of the photospheric magnetic field derived from numerous minute-by-minute images. From these maps, various solar coronal models calculate the solar wind parameters on the solar source surface (where the solar magnetic field lines are forced to be radial by the outflowing solar wind at around $2.5 R_{\odot}$) using different methods. For this, the extrapolation of the coronal field lines from the solar surface to the source surface is necessary: This can be done by, for example, the Potential Field Source Surface (PFSS) model ([Hundhausen, 1972](#)).

For example, the Wang-Sheeley-Arge (WSA) model ([Wang & Sheeley, 1990](#); [Arge & Pizzo, 2000](#)) determines the speed of the solar wind and the polarity of the interplanetary magnetic field based on empirical relationships. It derives the solar wind speed from magnetic field synoptic maps by looking at the magnetic flux tube expansion factor. [Schatten et al. \(1969\)](#) found that with higher magnetic divergence comes slower solar wind speed, while fast streams originate from regions with lower magnetic divergence. [Levine et al. \(1977\)](#) also concluded that the divergence of the solar magnetic field plays a significant role in the acceleration of the solar wind. Based on these findings, [Wang & Sheeley \(1990\)](#) published their method to derive solar wind speed directly from magnetograms, based on the apparent degree of flux tube expansions.

The WSA-ENLIL model ([Odstrcil, 2003](#); [Pizzo et al., 2011](#)) propagates solar wind parameters in 3D. The WSA model defines the outflow at the solar source surface, from which the ENLIL MHD model calculates the time-dependent parameters of the solar wind in the heliosphere in 3D. [Lee et al. \(2009\)](#) made an extensive comparison of the ENLIL MHD model using the WSA and the Magnetohydrodynamic Algorithm outside a Sphere (MAS; [Linker et al., 1999](#)) solar coronal

models as input with ACE solar wind velocity, density, dynamic pressure, and interplanetary magnetic field components between Carrington rotations 1999 and 2038, and found a good agreement for general large-scale solar wind structures. They also showed that latitudinal differences could be important to take into account while propagating solar wind parameters. This was also confirmed in [Owens et al. \(2019\)](#) and [Turner et al. \(2021\)](#).

In addition to the WSA and MAS models, the Alfvén Wave Solar Atmosphere model (AWSOM) produces solar wind data based on the Block-Adaptive Tree Solarwind Roe-type Upwind Scheme (BATS-R-US) general MHD code ([Tóth et al., 2012](#); [Sokolov et al., 2013](#); [van der Holst et al., 2014](#); [Meng et al., 2015](#)). Its solar corona model provides, among others, solar wind velocity, density, and magnetic field of the ambient corona below a solar distance of about 25 solar radii. It solves two-temperature MHD equations with Alfvén wave heating and heat conduction on a frame corotating with the Sun.

The solar wind parameters in the inner heliosphere are also modelled by the European heliospheric forecasting information asset (EUHFORIA) ([Pomoell & Poedts, 2018](#)). Its coronal model provides solar wind plasma parameters at 0.1 AU which are then used by its three-dimensional time-dependent magnetohydrodynamics model of the inner heliosphere as boundary conditions to determine the solar wind parameters up to 2 AU. Coronal Mass Ejections (CME) are also included in their solar wind predictions using the cone model, or with more complex CME flux rope models, such as the spheromak ([Verbeke et al., 2019](#)) and the Flux Rope in 3D (Fri3D; [Maharana et al., 2022](#)).

One of the difficulties of obtaining the parameters of the solar wind in the heliosphere in 3D is that with most of our instruments studying the Sun, we are only able to observe half of the solar surface at the same time – the disk visible from Earth. The STEREO A and B spacecraft were launched in 2006, and for several years, they could provide a complete picture of the properties of the solar wind in the ecliptic plane ([Kaiser et al., 2008](#)). Aside from this, helioseismic measurements can also provide information about the properties of the solar surface hidden from Earth. We would like to note as well that our current understanding of the solar polar regions is significantly incomplete, as those were not subject to detailed research by space probes since most solar wind measuring spacecraft resides near the ecliptic plane. The only major exception to this rule was the Ulysses mission launched in 1990, which captured the properties of the northern and southern polar regions of the Sun in three short snapshots, although from a relatively long distance (more than 200 million kilometres, i.e., 1.5 AU) from the solar surface ([Wenzel et al., 1992](#)). For the solar coronal models, accurate information about the polar regions would be necessary to get a complete picture of the Sun. Solar Orbiter ([Müller et al., 2020](#); [Solanki et al., 2020](#)) is expected to reach an inclination of 24 degrees with the help of gravitational assists from Venus by the end of 2025. If the mission is extended after 2025, it will even reach an inclination of 34 degrees relative to the solar equator. Its measurements and findings are expected to contribute significantly to the understanding of solar properties at higher heliospheric latitudes.

In our work, we determine the speed of the background solar wind in the inner heliosphere with a pressure-corrected ballistic extrapolation method using data from solar coronal

models as input. Arge & Pizzo (2000) used a similar improved ballistic method when validating the WSA model by propagating the solar wind speed from the source surface to near-Earth to compare it with Wind (Ogilvie & Desch, 1997) data. They propagated solar wind at a constant speed, while allowing interactions between the elements at every 1/8 AU, where the elements are recalculated using a weighting function. Ballistic propagation methods based on the WSA solution were also tested by others, who compared them with various MHD propagation methods and also spacecraft measurements (Riley & Lionello, 2011; Owens & Riley, 2017; Owens et al., 2020).

Accurate models and simulations of the heliosphere and solar wind interactions with different objects rely on a comprehensive understanding of the ambient solar wind. MHD models are often computationally expensive, while the ballistic method can predict the properties of the solar wind with similar accuracy, having the advantage that it is simple, requires less calculations, and it can be easily applied to the data of solar coronal models in order to obtain a fast and efficient prediction in 3D. Our 3D method considers the differential rotation of the Sun and also takes into account the latitude of the target which further improves the accuracy of our solar wind predictions; this way our work supports space missions not only in the ecliptic but also at higher latitudes. Since our aim is to predict the ambient background solar wind, in this paper, we focus on time periods with mostly quiet solar conditions in 2017.

2 Method

2.1 Propagation model

Our model can take the results of various solar corona speed maps as input data and propagate them outwards in consecutive propagation steps (Fig. 1) taking into account the differential rotation of the Sun. The duration of a propagation step (t_{step}) depends on the spatial resolution of the input map, and it is calculated as $t_{\text{step}} = T/N$, where T is the synodic rotation period of the solar corona at the given heliographic latitude and N is the number of longitude datapoints of the input data in one heliographic latitude, over one Carrington rotation.

The synodic rotation period of the corona at different latitudes are calculated based on the findings of Mancuso et al. (2020), in order to consider the differential rotation of the Sun. We fit the simplest possible function to the data points presented in their Figure 8, which can be written as follows:

$$T = A - B \cos(C\theta), \quad (1)$$

where $A = 27.51$, $B = -0.33$, and $C = 0.207$ are constants, and θ is the heliographic latitude in degrees. This equation is valid from $\theta = -50^\circ$ to $\theta = +50^\circ$, which means that our model provides accurate results between $\theta = \pm 50^\circ$.

To propagate the solar wind, first, the solar wind speed data are selected at a certain latitude at the solar distance of the input map (d_0). Knowing the solar wind speed (v) and the duration of a propagation step (t_{step}), the solar wind can be extrapolated radially using the ballistic propagation method (Opitz et al., 2009). The newly propagated solar wind data points will have a radial distance of $d_{n+1} = d_n + v \times t_{\text{step}}$, where d is the solar distance of the propagation steps and n marks the number of the propagation step.

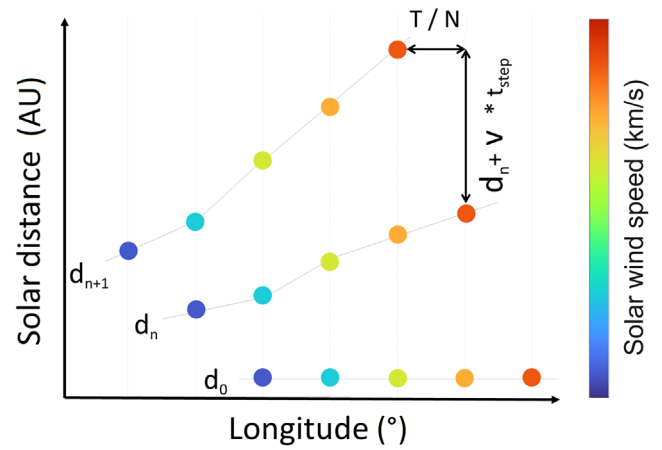


Figure 1. Solar wind ballistic propagation method. d_0 is the solar distance of the speed map, v is the solar wind speed. The radial distance of the propagated solar wind (d_n , where n is the number of the propagation step) is calculated based on the radial speed of the solar wind, while it is shifted in longitude according to the synodic solar rotation. $t_{\text{step}} = T/N$ is the duration of one propagation step, where T is the synodic rotation period of the solar corona, and N is the number of datapoints of the input data in one heliographic latitude, over one Carrington rotation.

The consecutive propagation steps, while extrapolated outwards, are also shifted in longitudes according to the rotation of the Sun. The duration of a propagation step is chosen in a way that the propagated and shifted datapoints will always fall onto the initial longitude grid. This way the calculated distances of the neighbouring propagation steps will be comparable with each other at each longitude (Fig. 1).

This process is carried out for every latitude between $\pm 50^\circ$ in order to determine the solar wind speed in 3D. Since our model extrapolates solar wind from the source surface, where the velocity is assumed to be radial, the effect of super-radial expansion is not considered in our model. From the resulting matrix, the extrapolated solar wind speed can be selected at any target position. However, the position of the target usually does not fall onto the distance-latitude grid of the matrix. To account for this, the two closest (higher and lower) distance and latitude to the target are selected, then a weighted average of the solar wind speed is calculated based on these values. In Figure 2a, we can see the extrapolated solar wind speed, where the longitude is on the x axis and the solar distance is on the y axis.

The result of this method is a continuous 3D dataset of solar wind speed. From this, we can select a subset at the location of a target, considering the constantly changing solar distance and latitude of the target. However, to overcome the limitations of the simple ballistic method, a pressure-correction is necessary in order to prevent faster solar wind packets from overtaking slower packets.

2.2 Pressure correction

High-speed streams (HSSs) are structures in the solar wind associated with coronal holes and characterized by an enhanced solar wind speed of approximately 500–800 km/s, lasting for several days (Snyder et al., 1963; Krieger et al., 1973;

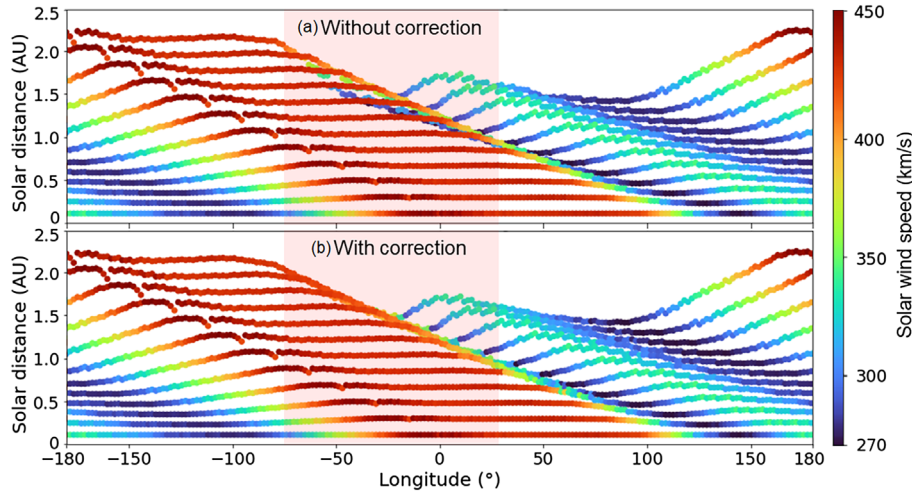


Figure 2. This figure compares the 3D ballistic propagation without pressure correction (a) and with pressure correction (b), using BATS-R-US data as input, over one Carrington rotation (CR = 2083). The x axis shows Carrington longitude, the y axis shows solar distance, the colorbar shows solar wind speed. In case of the uncorrected propagation, the faster solar wind streams can overtake the slower streams (i.e., around longitude -50° to 0°). During the speed correction, the speed is recalculated to account for this negative effect of the simple ballistic propagation.

Sheeley et al., 1976; Grandin et al., 2019). The simple ballistic method, as it idealizes the propagation of solar wind in the heliosphere, assumes a constant speed during radial solar wind extrapolation. This means that when we extrapolate the solar wind using the simple ballistic method, the propagated high-speed solar wind streams can overtake slower streams in front of them. However, since the solar wind streams emanating from the Sun are threaded by magnetic field lines, the high-speed streams are prevented from overtaking slower solar wind streams. This leads to plasma compression and a pile-up of the magnetic field lines where the interaction occurs, creating a structure in the solar wind called stream interaction region (SIR). At large enough solar distances, the pressure waves created by the compression can steepen into forward and reverse shocks, ahead and behind the SIR (Gosling & Pizzo, 1999). These compressed regions will rotate with the Sun, forming spirals near the solar equator. If this structure is recurring with a ~ 27 -day period (the synodic solar rotation when viewed from Earth), it is referred to as a corotating interaction region (CIR).

Our improved solar wind propagation model considers the interaction between fast and slow solar wind streams by applying a speed correction during the extrapolation, based on the pressure difference between the two different solar wind plasma. During the correction, we recalculate the radial velocities of the colliding fast and slow solar wind streams that prevents them from overtaking each other in the model.

We determine the pressure-correction for fully developed CIRs, because it provides a reasonable assumption, and already prevents the unphysical interpenetration of plasma parcels. For young emerging CIRs close to the Sun, other effects should also be considered. To work out the characteristics of the correction, it is expedient to investigate CIRs from a coordinate system moving together with the CIR's stream interface, which separates the fast and slow solar wind streams. If the velocity of the stream interface is v_0 , the velocities of the slow and fast solar wind streams are v_1 and v_2 , respectively, then the velocities of the slow and fast streams relative to the stream interface are

$u_1 = v_1 - v_0$ and $u_2 = v_2 - v_0$. In this coordinate system, both streams are traveling towards the stream interface. When they reach the interaction region, their speed abruptly changes to zero. The rate of momentum change can be written as follows:

$$\frac{\Delta I}{\Delta t} = \rho u A \frac{\Delta s}{\Delta t} = \rho u^2 A = p_d A, \quad (2)$$

where ρ is the density, s is the displacement, p_d is the dynamic pressure of the plasma, and A is the area in which the interaction between the fast and slow solar wind streams takes place. Since the momentum is conserved, this rate must be equal on the two sides of the interface:

$$\frac{\Delta I_1}{\Delta t} = \frac{\Delta I_2}{\Delta t}. \quad (3)$$

Therefore we can say, that $p_{d1} = p_{d2}$, and $\rho_1 u_1^2 = \rho_2 u_2^2$.

After solving this equation and transforming back to the original coordinate system we get:

$$v_0 = \frac{1}{1-r} (v_1 - r v_2 + \sqrt{r} (v_2 - v_1)), \quad (4)$$

where $r = \rho_2/\rho_1$ is the density ratio of the fast and slow solar wind plasma. The physically meaningful solution is that, which provides a positive v_0 . In the limit of $\rho_2 = \rho_1$, this gives:

$$v_0 = \frac{v_1 + v_2}{2}. \quad (5)$$

Knowing the solar wind speed and density, the speed of the CIR stream interface can be calculated. We compare the distances travelled by radially adjacent plasma packets at every subsequent propagation step and at every longitude of the input solar wind speed map. If there is an overtake ($d_n > d_{n+1}$ at the same longitude), we carry out the speed correction, and the speed of the slower and faster solar wind packets participating in the overtake is recalculated using equation (4). In case of large speed differences, it is also possible that non-adjacent propagation steps overtake each other. In this case, we carry out the

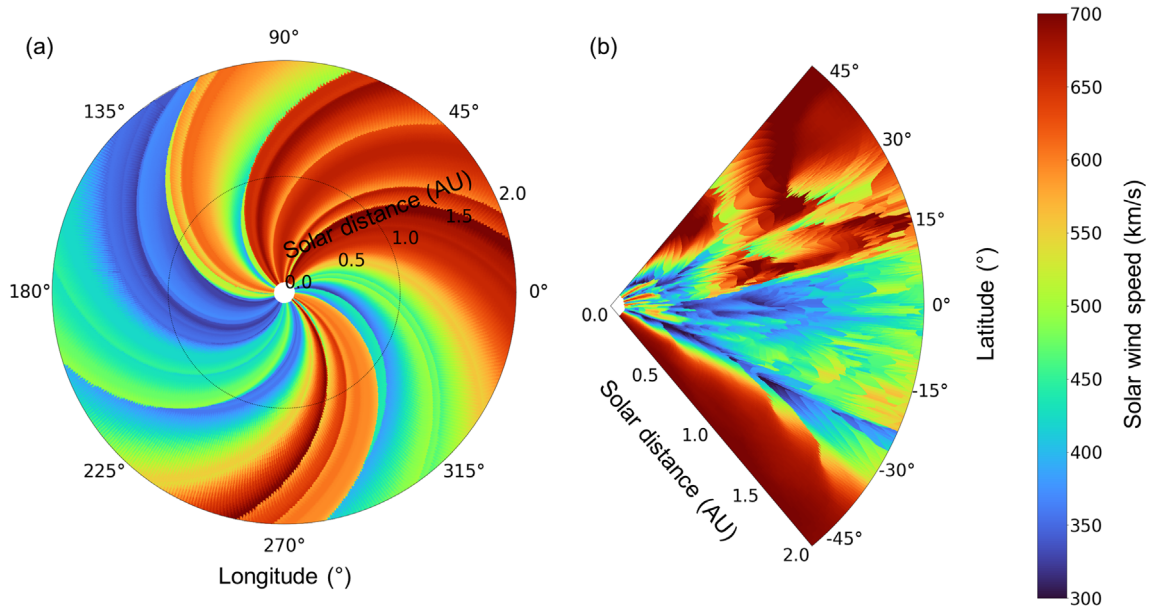


Figure 3. Propagated 3D ballistic solar wind speed in the ecliptic (a) and at a Carrington longitude of 180° (b). The figure shows a snapshot of the background solar wind conditions in January 2017 between 21.5 R_S and 2 AU.

speed correction over multiple propagation steps that participate in the overtake. In the absence of solar wind density data, equation (5) can be used to recalculate the propagated solar wind speed, if we rely on the assumption that $\rho_1 = \rho_2$, however, our model can easily be extended to use the more sophisticated expression, if the coronal model can also provide density data on the source surface. In Figure 2, we compare the ballistic propagation with and without correction. It can be seen that the correction prevents the solar wind streams from overtaking each other.

3 Validation

With our 3D, pressure-corrected ballistic method, our aim is to propagate the ambient solar wind. In this paper, we focus on a time period with fairly low solar activity, during the descending phase of Solar Cycle 24, in 2017, so solar transient events, such as coronal mass ejections, don't affect the results negatively. Our method provides solar wind speed at any given location in the inner heliosphere and can take various solar coronal models as input data. Besides the data of solar coronal models, the pressure-correction can also be applied to the propagated data of different spacecraft travelling in the solar wind and measuring its parameters, although in this case, the propagation can be at most two-dimensional. In this section, we present the results of our model calculated using the WSA and AWSoM models as input data. We validate our results with the measurements of the ACE spacecraft located at the L_1 point of the Sun-Earth system, at a heliocentric distance of 0.99 AU.

3.1 WSA

We mainly calculated solar wind speed for the year 2017 using WSA (Wang & Sheeley, 1990; Arge & Pizzo, 2000) speed maps as input data which are readily available in the

integrated Space Weather Analysis (iSWA) catalog in a form of hourly speed maps, created from GONG_Z synoptic field maps. The GONG_Z maps are GONG magnetograms corrected for zero-point uncertainty that is necessary due to the inconsistencies of the magnetogram. The WSA model is also available for runs at the Community Coordinated Modeling Center (CCMC) at <https://ccmc.gsfc.nasa.gov/>.

The solar wind speed maps were downloaded with a five-day temporal resolution, while the resolution in latitude and longitude is 2°. This allows a time resolution (t_{step}) of approximately 3.6 h. The latitudes and longitudes are computed in the Heliographic Carrington frame, where the origin is the centre of the Sun, the Z-axis (+90° latitude) is aligned with the Sun's north pole, and the X-axis and Y-axis rotate with a period of one Carrington rotation. Each speed map covers and produces data for a full Carrington rotation. From every map, the data of the first 66° (approximately $5 \times 360/7$) of longitudes were used for the propagation, so that there are no overlaps between the data of different maps. In this case, we relied on the assumption that $\rho_1 = \rho_2$ and used equation (5) to carry out the solar wind speed correction. The results can be visualized in 3D and 2D images or animations or can be plotted as one-dimensional time series. In Figure 3, we demonstrate the modelled solar wind speed from WSA input data generated during one Carrington rotation between 28 December 2016 and 24 January 2017.

We compared the results of our model to the solar wind ion speed measured by the Solar Wind Electron, Proton and Alpha Monitor (SWEPAM) instrument (McComas et al., 1998) of the NASA Advanced Composition Explorer (ACE) spacecraft (Stone et al., 1998) located at the L_1 point of the Sun-Earth system, at a heliocentric distance of 0.99 AU to validate our dataset. In the validation process, we used the Level 2 SWEPAM 64-second averaged solar wind ion speed obtained from the ACE Science Center. The validation was carried out for 2017. Our method only predicts the background solar wind; therefore, the removal of non-corotating effects, such as ICMEs

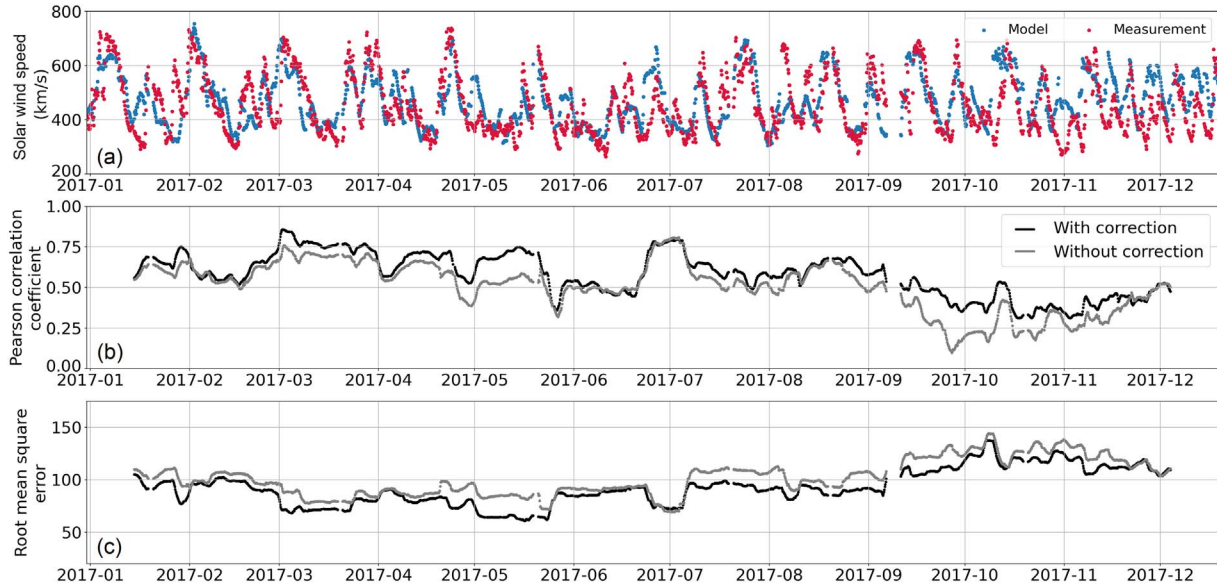


Figure 4. ACE SWEPAM solar wind ion speed measurements (red dots) and pressure corrected 3D ballistic solar wind speed (blue dots) in 2017 with a temporal resolution of 3.6 h (a). Non-corotating effects such as ICMEs were removed from the datasets. The correlation coefficient (b) and the root mean square error (c) are shown with a sliding window of one Carrington rotation between the ACE solar wind speed and the pressure corrected (black dots) and the non-pressure corrected (grey dots) ballistic solution.

from the measurements was necessary. During the validation process, we removed these effects from the ACE data based on our ICME catalogue (Dalya et al., 2023). The input speed maps are provided at a solar distance of $21.5 R_s$. The WSA model computes the speeds from the spatial configuration of the magnetic field, which does not consider the propagation time of the solar wind from the altitude of the GONG magnetic maps to the altitude of the source surface. The difference is insignificant as long as the source surface is placed into the lower corona, but the source surface altitude used in this study ($21.5 R_s$, ~ 0.1 AU) means that the solar wind would need several hours to propagate from the lower corona to the source surface. This delay can influence the performance of the propagation method. The simplest way to consider the delay caused by this effect is to calculate the arrival times at the location of the target from speed maps projected back to the solar surface. We calculated both alternatives (starting the propagation from the source surface and from the back-projected maps). The second choice provided an overall better, with an approximately 10% increase in correlation with ACE measurements.

We compared the propagated solar wind speed selected at the position of the ACE spacecraft with ACE solar wind measurements in 2017 (Fig. 4). Using the measurements of the Wind and ACE spacecraft near-Earth (Grandin et al., 2019), identified 33 high-speed streams in the solar wind during 2017, with speeds ranging from 500 to 750 km/s. For a comparison of our 3D model with ACE measurements, a pressure correction is necessary to properly extrapolate these high-speed streams travelling in the slower background solar wind with an average speed of 350–400 km/s. In Figure 4a, the modelled solar wind speed calculated using pressure-correction is illustrated with blue dots, while the ACE measurements are shown with red dots. The model shows a good general correlation with the measurements. It predicts the arrival, duration, and

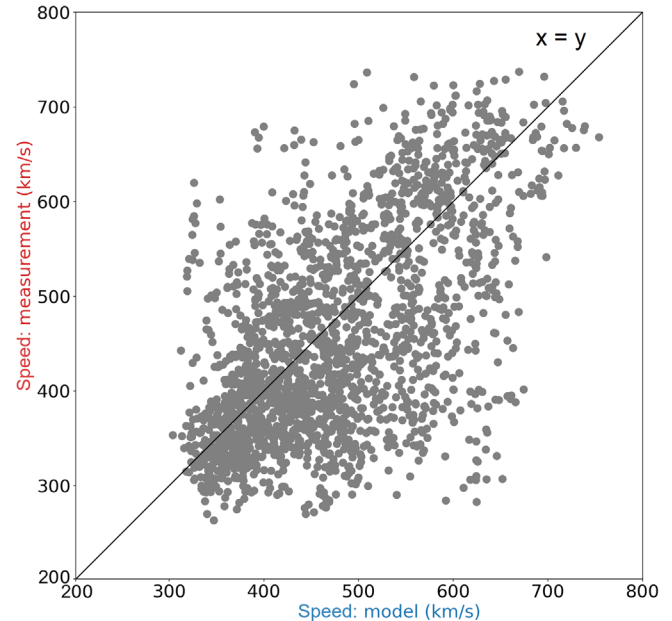


Figure 5. Correlation between our 3D pressure corrected ballistic model and the ACE solar wind speed measurements in 2017. The Pearson correlation coefficient is 0.59 for the full year, which indicates a moderate correlation between the two datasets.

maximum speed of CIRs. The speed of the ambient solar wind between CIRs is also predicted well.

The Pearson correlation (Freedman et al., 2014) between our model and the ACE measurements is shown in Figure 4b, calculated with a sliding window of one Carrington rotation, for both the pressure-corrected and the non-pressure-corrected

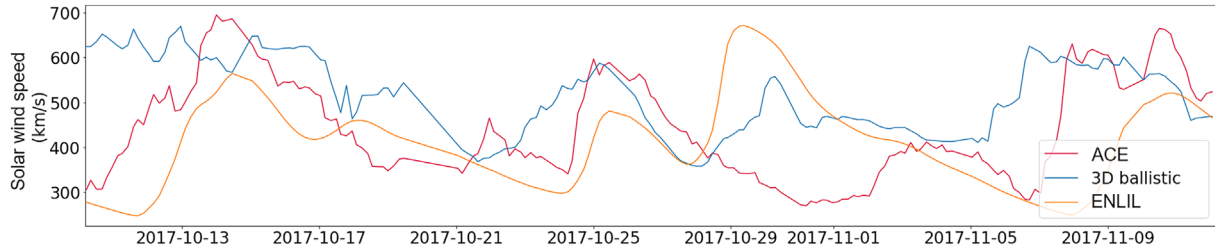


Figure 6. Pressure corrected 3D ballistic model using WSA speed maps as input data (blue line) compared to ACE measurements (red line) and the solar wind speed of the ENLIL MHD model (orange line).

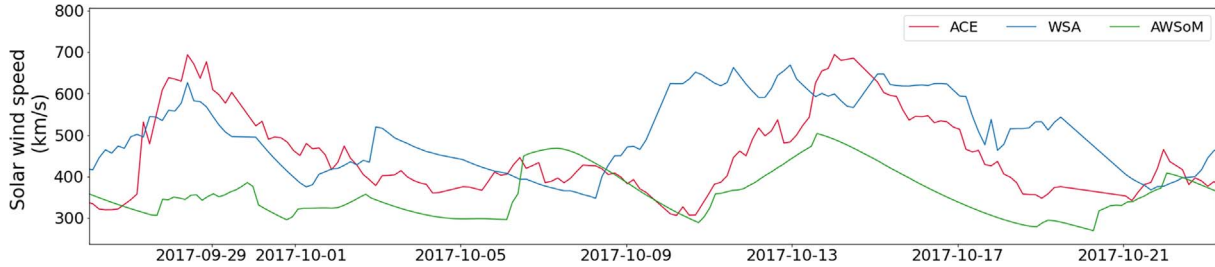


Figure 7. Comparing the ACE solar wind measurements near-Earth (red line) and the 3D ballistic propagations with WSA (blue line) and AWSOM (green line) solar wind speed as input data.

solution. For most of 2017, the model can predict the measured solar wind speed very well, with the pressure-corrected solution giving a better overall correlation. The Pearson correlation coefficient for the pressure-corrected solution is around $r = 0.6$ that suggests a moderate correlation between our model and the ACE dataset. However, the correlation gradually breaks down in the last months of 2017, where it is around $r = 0.4$ with pressure correction, and $r = 0.3$ without the pressure-correction. This can be explained by the Earth passing through the solar equator in early June and December. In these periods, even small fluctuation can lead to such configurations, in which the Earth is located on the opposite side of the current sheet with respect to its position in the model. This explanation is also supported by the fact that at around June, the correlation also decreases, from around $r = 0.75$ to $r = 0.5$ in case of the pressure-corrected solution. The correlation coefficient calculated for the entire time period (Fig. 5) is $r = 0.59$ ($p < 0.001$) for the pressure-corrected model, and it equals to $r = 0.51$ without pressure correction. We also calculated the root mean square error (RMSE) between the measured and propagated datasets for 2017. The RMSE is also illustrated in Figure 4c for 2017, calculated with a sliding window of one Carrington rotation.

We also compared our pressure-corrected ballistic model to ENLIL (Odstrcil, 2003; Pizzo et al., 2011) solar wind speed between 10 October 2017 and 12 November 2017 (Fig. 6). The two models give slightly different results, however both models have a good general correlation with the ACE measurements during this month. Since both models use the WSA speed maps as input data, the same structures appear in both, although shifted in time and magnitude due to the different properties of the models.

3.2 AWSOM

In this paper, we mainly worked with WSA data, due to its easy availability, however our model is applicable to the data of

any kind of solar coronal model. Therefore, we also tested our model with the AWSOM (Tóth et al., 2012) MHD solar coronal model as input data. The model is available for run-on-request at CCMC at https://ccmc.gsfc.nasa.gov/models/SWMF~AWSOM_R_1.0/. Its input is also the synoptic maps produced by the various solar telescopes and telescope networks as for the WSA model. The AWSOM dataset is available at a solar distance of $24 R_S$ in HEE (Heliocentric Earth Ecliptic) coordinates. It has 201 datapoints over one Carrington rotation, resulting in a longitude resolution of 1.8° . This means a time resolution of approximately 3.5 h. The resolution in latitudes is 0.9° .

The result of the propagation is correlated with both the ACE measurements and the solar wind speed calculated using the WSA dataset as input data for one Carrington rotation starting in September 2017 (Fig. 7). The extrapolated solar wind speed generated from the two different input data are similar, however the speed and the arrival times of the CIR structures deviate slightly from each other.

4 Summary

In this paper, we presented a 3D method for extrapolating background solar wind in the inner solar system with a speed, corrected ballistic extrapolation method using solar coronal models as input data, while also considering the differential rotation of the Sun. The applied pressure-correction successfully prevents the unphysical interpenetration of plasma packets in the simulation. Considering the differential rotation of the corona improves the fit compared to that computed with rigid rotation. Our model works with any input data that can provide the solar wind speed on the source surface. The method can be used on various 2D solar corona maps to provide solar wind speed values in 3D in the heliosphere, between latitudes of

$\pm 50^\circ$. The Solar Orbiter spacecraft could reach an inclination of 34° after 2025; therefore, the study of the solar wind in the inner solar system becomes possible even at higher heliographic latitudes, which could be aided by 3D solar wind models.

We validated our model using ACE solar wind measurements provided by the ACE spacecraft during a period of relatively low solar activity, in 2017. The correlation is significant between the ACE measurements and our pressure-corrected model, for long time periods: the Pearson correlation coefficient is around 0.75 for most of 2017. It decreases to around 0.4 in the last three months of 2017, that could be explained by the Earth moving through the equatorial plane of the Sun in early December. Due to the small fluctuations of the current sheet during this time period, there is a greater chance for the Earth to be located on the other side of the current sheet than it is located according to the model.

We compared the solar wind speed calculated by our model with WSA and with AWSOM datasets as input data. The results depend on the source of the input solar wind data; the empirical and MHD models predict slightly different solar wind speed.

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