SWASTi-SW: Space Weather Adaptive Simulation Framework for Solar Wind and Its Relevance to the Aditya-L1 Mission

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Received 2022 April 7; revised 2022 July 11; accepted 2022 July 25; published 2022 September 2

Abstract

Solar wind streams, acting as a background, govern the propagation of space weather drivers in the heliosphere, which induce geomagnetic storm activities. Therefore, predictions of the solar wind parameters are the core of space weather forecasts. This work presents an indigenous three-dimensional (3D) solar wind model (SWASTi-SW). This numerical framework for forecasting the ambient solar wind is based on a well-established scheme that uses a semiempirical coronal model and a physics-based inner heliospheric model. This study demonstrates a more generalized version of the Wang–Sheeley–Arge relation, which provides a speed profile input to the heliospheric domain. Line-of-sight observations of GONG and Helioseismic and Magnetic Imager magnetograms are used as inputs for the coronal model, which in turn provides the solar wind plasma properties at 0.1 au. These results are then used as an initial boundary condition for the magnetohydrodynamics model of the inner heliosphere to compute the solar wind properties up to 2.1 au. Along with the validation run for multiple Carrington rotations, the effect of variation of specific heat ratio and study of the stream interaction region (SIR) are also presented. This work showcases the multidirectional features of SIRs and provides synthetic measurements for potential observations from the Solar Wind Ion Spectrometer subsystem of the Aditya Solar wind Particle Experiment payload on board ISRO’s upcoming solar mission Aditya-L1.

Unified Astronomy Thesaurus concepts: Solar wind (1534); Magnetohydrodynamical simulations (1966); Interplanetary magnetic fields (824)

Supporting material: animation

1. Introduction

The study of the influence of the Sun on Earth has become an essential area of research globally, known as space weather. The effects of space weather can disrupt electric power supply, perturb navigation systems, interrupt satellite functionality, and be hazardous to astronaut health. The extremely energetic space weather events could even impact the global economy. Therefore, the importance of space weather forecasting is recognized not only by the research community but also by government and industry stakeholders (Schrijver et al. 2015).

To mitigate the adverse effects of space weather, it is crucial to understand the physics to prepare our timely rational response. The existing observatories provide the details of the near-solar-surface region (e.g., Solar and Heliospheric Observatory, STEREO, Solar Dynamics Observatory (SDO), GONG, the near-Earth region (e.g., ACE, Wind, DSCOVR), and the inner heliospheric region (e.g., Parker Solar Probe, Solar Orbiter)). These observatories present a good starting point for the study but do not produce the required insight of arrival time of the energetic space weather events. Hence, to bridge this gap, numerical models are necessary, which could use the observed data and forecast hazardous events like coronal mass ejections (CMEs), solar energetic particles (SEPs), and stream interaction regions (SIRs), among others. Solar wind streams, acting as a background, govern the propagation of these events in the heliosphere and drive geomagnetic storm activities. Therefore, predictions of the solar wind parameters are the core of space weather forecasts.

The method of inner heliospheric modeling of solar wind can be broadly classified into three categories: empirical, semiempirical, and magnetohydrodynamics (MHD) based simulation. Empirical models (e.g., PDF, Bussy-Virat & Ridley 2014; PROJECTZED, Riley et al. 2017; AnEn, Owens et al. 2017) use a probabilistic forecasting approach, which is framed by analyzing solar wind observations at the Sun–Earth L1 Lagrangian point. The semiempirical models (e.g., ESWF, Reiss et al. 2016; WSA, Arge & Pizzo 2000) employ an empirical relation of solar wind speed based on the observation of coronal holes. On the other hand, simulation models (e.g., MAS, Riley et al. 2001; ENLIL, Odstrcil 2003; SWMF, Tóth et al. 2005; SWIM, Feng et al. 2010; SUSANNO, Shiota et al. 2014; EUHFORIA, Pomoell & Poedts 2018; Narechiana et al. 2021) are physics-based models that use photospheric magnetograms to determine plasma properties in the heliosphere. According to the assessment of MacNeice et al. (2018), the accuracy of empirical models surpasses the results of semiempirical and simulation models. The empirical models are relatively less intensive computationally and give more accurate results. However, these models offer a limited number of plasma properties at the L1 location. Though simulation models are computationally expensive, these models provide an understanding of fundamental physics that is essential for preparing a sensible response against the space weather effects. A coupled two-domain procedure is followed by almost all simulation models. In some cases MHD codes are used for both
domains (e.g., MAS, SWMF, ENLIL-MHD, SWIM), and in some cases, the Wang–Sheeley–Arge (WSA) model is used in the coronal domain (e.g., ENLIL-WSA, SUSANOO, EUHFORIA; Narechania et al. 2021).

This work is the first step toward our central objective, i.e., to develop a full-fledged data-driven Space Weather Adaptive SimulA tion (SWASTi) framework. In this paper, we present a solar wind model, SWASTi-SW, which is the first part of this modular framework. This newly developed physics-based solar wind model uses an updated WSA approach in the coronal domain and an MHD code in the inner heliospheric domain. The MHD domain uses the PLUTO code (Mignone et al. 2007) to compute the plasma properties in the inner heliosphere. An earlier assessment of usage of the PLUTO code for solar wind prediction was done in the two-dimensional pilot study by Kumar et al. (2020), in which they compared the results with other extrapolation models using the WSA relation. In this three-dimensional work, a more generalized version of the WSA relation is used, along with the more robust and flexible coronal model. For coronal modeling, the PFSSPY (Stansby et al. 2020) Python package has been used in this work. The emphasis has been to achieve satisfactory results in modest computational time. This paper highlights the technical specifications and implementation of the model to forecast and assess the ambient solar wind plasma properties at L1. Additionally, the paper demonstrates the prospect to compliment the in situ measurements of Aditya-L1.

Aditya-L1 is India’s first dedicated solar mission to be placed at a halo orbit around the first Lagrangian point of the Sun–Earth system. The Solar Wind Ion Spectrometer (SWIS) and SupraThermal & Energetic Particle Spectrometer (STEPs) are the two subsystems of the Aditya Solar wind Particle Experiment (ASPEX) payload on board Aditya-L1. Brief details regarding the Aditya-L1 mission (Seetha & Megula 2017) and the ASPEX payload (Janardhan et al. 2017; Goyal et al. 2018) have been reported elsewhere. The novelty of ASPEX is multidirectional, high-cadence, and proton-alpha separated measurements. In this work, the potential solar wind plasma measurements by SWIS have been simulated based on the modeled outputs to understand the directional variation of solar wind proton fluxes during the passage of the SIR or corotating interaction region (CIR).

The paper has been organized in the following manner. The methodological description of the framework is discussed in Section 2. The model capability, along with the comparison of results with observations at L1, is presented in Section 3. The assessment of observation of ASPEX using SWASTi-SW has been given in Section 4. A discussion on results, limitations, challenges, and forthcoming projects is contained in Section 5.

2. SWASTi-SW

This numerical framework for forecasting and assessing the ambient solar wind is based on a well-established scheme that uses a semiempirical coronal model and a physics-based inner heliospheric model. Figure 1 shows the processes involved in SWASTi-SW, from photospheric magnetogram input to computing plasma properties in the inner heliosphere. The spatial range of the coronal domain goes from 1.0 to 21.5 $R_\odot$ (0.1 au) and that of inner heliosphere from 0.1 to 2.1 au. The mentioned scheme is now commonly used for the simulation of the Sun–Earth connection, for example, in ENLIL, SUSANOO, and EUHFORIA. Though a similar scheme is followed by these existing models, they differ in defining crucial parameters in both the subdomains. The details of subdomains of SWASTi-SW have been described in the following subsections.

2.1. Submodel for Corona

The primary aim of the coronal domain is to provide the inner boundary condition for the inner heliospheric model; therefore, the radial distance of this boundary ($R_{\text{in}}$), from the center of the Sun, decides the range of the coronal model. $R_{\text{in}}$ should essentially lie in the region where solar wind plasma becomes supersonic as well as super-Alfvénic. Goelzer et al. (2014) showed that this distance is correlated with the sunspot number and varies from 15 $R_\odot$ at solar minima to 30 $R_\odot$ at solar maxima. As in this work we have mainly focused on the solar minima regime, taking this distance to be 21.5 $R_\odot$ (i.e., 0.1 au) is a physically suitable estimate. Therefore, the coronal domain’s radial coverage extends to 0.1 au, while its latitudinal coverage and longitudinal coverage range from $-90^\circ$ to $90^\circ$ and from $0^\circ$ to $360^\circ$, respectively, in the heliographic Carrington frame.

SWASTi-SW uses a synoptic magnetogram as input and a modular approach for coupling potential field source surface (PFSS; Altschuler & Newkirk 1969) and Schatten current sheet (SCS; Schatten 1971) codes. This modular method facilitates an option of using PFSS alone or a coupled PFSS+SCS. Both versions rely on the empirical relation of the WSA model to calculate the solar wind speed profile at $R_{\text{in}}$.

2.1.1. Input Magnetogram

The only observational input in our model is the full-disk photospheric magnetogram. Therefore, it becomes important to carefully choose the suitable type of input magnetogram. In this work, we have used integral Carrington rotation (CR) synoptic maps provided by NSO-GONG (filename prefix: mrmqs) and SDO’s Helioseismic and Magnetic Imager (HMI) (JSOC series: hmi.synoptic_mr_polfil_720s). The integral synoptic maps are calibrated by merging standard line-of-sight (LOS) maps and remapping into appropriate longitude in the Carrington frame. For each Carrington longitude of the synoptic map, standard magnetograms near the central meridian, of that longitude, are averaged using a weighting factor (e.g., GONG uses cosine$^4$ (longitude)); for more details see Hill (2018) and Scherrer et al. (2012). The advantage of using integral CR synoptic maps is that each point along the $x$-axis (longitude) represents the location of Earth during that CR period, thereby providing the required input for studying the ambient solar wind at 1 au in lesser computational time.

Both GONG and HMI magnetograms provide magnetic fields at the solar surface over linearly spaced grid points in longitude ($x$-axis) and equally spaced in sine(latitude) grid points in latitude ($y$-axis). The used GONG magnetogram has a resolution of $360 \times 180$ points, whereas that of HMI is $720 \times 360$ points in the phi-theta plane.

2.1.2. Potential Field Source Surface Model

In the lower solar corona, we have used the PFSS model to solve for the global magnetic fields. It is based on a simple approach that exercises the uniqueness theorem of the Laplace equation by assuming the electric current to be negligible. This approximation is reasonable in the lower corona, where plasma is force-free (Gary 2001) and most of the transequatorial field lines are current-free (Tadesse et al. 2014), especially in quiet
and weak active regions. Though more realistic, but complex, models exist (see Wiegelmann et al. 2017, and references therein), observational tests (Schrijver & Derosa 2003; Liu & Lin 2008) and comparative studies (e.g., Riley et al. 2006) depict that the PFSS model is adequate for examining large-scale solar and heliospheric fields.

PFSS solves the Laplace equation from the solar surface (boundary condition provided by the input magnetogram) to source surface (from where the field is prescribed to be radial). Traditionally, a spherical harmonic expansion approach is implemented (e.g., Altschuler et al. 1977; Hakamada 1995; Nikolic 2019; WSA-ENLIL; EUHFORIA). However, this technique gives rise to ring-like patterns and is also sensitive to the choice of the number of spherical harmonics (Tóth et al. 2011; Asvestari et al. 2019). An iterative finite-difference scheme has also been applied to solve PFSS (van der Holst et al. 2010; Caplan et al. 2021), and it shows no signature of a ringing effect and can be favored over the harmonic approach, especially near strong magnetic field regions. In this work, we have used PFSSPY, which is based on the method of van Ballegooijen et al. (2000). The PFSSPY code is a finite-difference solver and hence allows the model to escape the ringing effect disadvantage occurring in the spherical harmonic approach.

PFSSPY is solved on a rectilinear grid that is equally spaced in \( \ln(r) \), \( \cos \theta \), and \( \phi \) in spherical coordinates \( (r, \theta, \phi) \). We have used a grid resolution of \( 100 \times 181 \times 361 \) to solve for field lines from \( 1 R_s \) to source surface radius \( (R_{ss}) \), which is \( 2.5 R_s \) in our case. The magnetic field lines are traced in two sets: first, from the inner boundary \( (1 R_s) \) to outer boundary \( (2.5 R_s) \) at the mentioned resolution, which gives the coronal hole perimeter as both open and closed field lines are traced; and second, from source to solar surface at higher resolution of \( 100 \times 181 \times N \), where \( N \) is the number of hours in CR. In the later set, there are only open field lines originating from inside the coronal hole, whose perimeter is traced by the first set. This two-set tracing approach provides greater resolution of field lines at the source surface.

Figure 2 shows the results of the PFSS model, projected in the \( \theta - \phi \) plane. Panel (a) shows the computed input radial magnetic field from the GONG magnetogram, and panel (b) shows the radial magnetic field at the source surface \( (R_{ss}) \). In panel (b), the blue line in the middle represents the magnetic polarity inversion line, which effectively shapes the current sheet in the heliosphere. Panel (c) depicts the two-set tracing approach of magnetic field lines. The tracing from \( 1 R_s \) to \( R_{ss} \) gives the region of closed field lines (light and dark gray) and the coronal hole boundary (the green area) at solar surface. Further, the tracing of open field lines (cyan and orange) from \( R_{ss} \) to \( R_s \) provides their footpoints (red circles) inside the coronal hole area. The black line in the middle is the location of Earth for CR2081. Hence, the figure illustrates the origin points of the field lines that will reach Earth.

2.1.3. Schatten Current Sheet Model

In the upper corona (i.e., beyond \( R_{ss} \)), plasma beta becomes greater than unity (Gary 2001) and most of the field lines become almost radial, as plasma pressure starts dominating the dynamics. To incorporate the nonzero current region near the polarity inversion territory, Schatten (1971) proposed the SCS model. It requires solving another Laplace equation with inner boundary conditions given by PFSS and outer boundary extending to infinity, leading the fields to vanish. The inner boundary distance of SCS \( (R_{ss}) \) is usually taken to be less than \( R_{ss} \) to avoid the kink formation at the interface. This technique results in improved solar wind structures at 1 au sometimes, but most of the time it does not affect solar wind predictions (McGregor et al. 2008). In SWASTi-SW, the default setup is \( R_{ss} = R_{ss} \), but it can be changed by the user at the run-time.

There are two main advantages in using coupled PFSS+SCS over PFSS alone. It provides more realistic magnetic field values in the upper corona, and it facilitates more accurate
and closed, which is similar to Equation 2.

\[
V_{R_{\text{in}}} = \frac{V_{\text{max}}}{(1 + f_s)^\beta} \times \left[ 1.0 - 0.8 \exp \left( -\left( \frac{d}{w} \right)^\beta \right) \right]^3 \text{ km s}^{-1},
\]

where

\[
f_s = \frac{R^2}{R^2} \times B_s(R_s^2, \theta, \phi),
\]

which is similar to Equation (2) of McGregor et al. (2011). In Equation (1), \(V_{\text{min}}, V_{\text{max}}, \beta,\) and \(w\) are independent parameters, whereas \(f_s\) and \(d\) are the areal expansion factor of the flux tube and the minimum angular separation of the footpoint from the coronal hole boundary, respectively. A similar form of the WSA velocity relation is also being used by other models (e.g., WSA-ENLIL, EUHFORIA; Narechania et al. 2021), but each uses a different set of values of independent parameters.

The role of \(w\) is to normalize the minimum angular distance of the flux tube footpoint from the open flux boundary \(d\), and \(\beta\) controls the effect of this distance on solar wind speed relation \(V_{R_{\text{in}}})\), whereas \(V_{\text{min}}\) and \(V_{\text{max}}\) regulate the minimum and maximum value of \(V_{R_{\text{in}}})\). Figure 3 shows the graphical representation of the functional form of \(V_{R_{\text{in}}})\). Two main features are to be observed here. As the value of \(d\) increases from 0° (i.e., field lines originating from close to the edge of coronal hole), the value of \(V_{R_{\text{in}}} \) does not change much, regardless of the value of \(f_s\), and after a threshold value of \(d\), \(V_{R_{\text{in}}} \) depends only on \(f_s\). Additionally, in between these two values, both \(d\) and \(f_s\) increase monotonically and contribute to \(V_{R_{\text{in}}} \). And to properly use the capability of the WSA model, the speed empirical relation has to be dependent on both \(d\) and \(f_s\). Parameter \(w\) regulates the value of \(d\) from which the second feature starts, and \(\beta\) determines the threshold value of \(d\). The increase (decrease) in \(V_{\text{min}} \) shifts the graphs upward (downward), and the variation in \(V_{\text{max}} \) shifts the peak. Therefore, these four independent parameters in the empirical relation are critical in getting an accurate solar wind speed estimation at 0.1 au.

Out of four free parameters, the optimal value of \(w\) is the most volatile, as for different grid resolutions the value of \(d\) changes and so will \(w\), to effectively normalize it. With an attempt to take a more generalized approach, we replaced the value of \(w\) with the median of \(d\). Keeping the focus on the field lines that reaches the location of Earth, we calculated \(d\) and \(f_s\) (now \(d_E\) and \(f_{E,s}\) for this case) values for only those flux tubes and checked the variability features in solar wind. As shown in Figure 4, this adapted method displays the same kind of features as in Figure 3. Moreover, by fixing the values of \(V_{\text{max}}\) and \(V_{\text{min}}\) (by default 725 and 240 km s\(^{-1}\) for the HUX run), we can presume, from Figure 4, that the optimal value of \(\beta\) should

![Figure 2](image-url)
But to find the optimal value of $\beta$ precisely, comparison of the speed profile at the first Lagrangian point of the Sun–Earth system ($L_1$) with observational data is required. For comparison with OMNIWeb data, we used the Heliospheric Upwind eXtrapolation (HUX) model (Riley & Lionello 2011), for a range of values of $\beta$. HUX is a simple one-dimensional upwind extrapolation technique that neglects the effects of magnetic field, gravity, and pressure gradient. The HUX model gives a very good match for speed results at 1 au (Riley & Issan 2021), and also in much less computational time. To find the optimal value of $\beta$ for a given CR, we calculated the solar wind profile at 1 au ($V_{\text{HUX}}$) by varying $\beta$ from 0.75 to 1.75 in 20 equal steps and compared it with observed data ($V_{\text{OBS}}$). For this initial study we restricted the

Figure 3. Variation of solar wind speed for the range of values of $d$ and $f_s$ based on a different set of values of $\beta$ and $w$ while keeping $V_{\text{min}}$ and $V_{\text{max}}$ constant (240 and 725 km s$^{-1}$), $d$ varies from 0° to 12°, and the value of $f_s$ goes from 1 (green at top) to 99 (red at bottom) with increments of 1. The dotted vertical lines are placed corresponding to values of $w$. For $\beta = 2$, $V_{\text{HUX}}$ becomes independent of $d$ at a much smaller value as compared to the $\beta = 1$ case.

Figure 4. Graphical depiction of solar wind speed variation with different values of $\beta$ at 0.1 au for CR2081. Speed profiles are of those field lines that reach sub-Earth points (location of Earth in Carrington heliographic coordinates). Here, $V_{\text{min}} = 240$ km s$^{-1}$, $V_{\text{max}} = 725$ km s$^{-1}$, and $w = 0.54$ (median of $d_E$). For each field line, values of $d_E$ and $f_s$ are calculated from the coronal model, and the vertical dotted line represents the value of $w$. $f_s$ has been distributed in three equal bins (green, blue, and red), with green showing the lowest (from top) and red showing the largest values (at bottom).
range to ±0.5 around the most used value of β, i.e., 1.25 (e.g., van der Holst et al. 2010; Riley et al. 2015; Pomoell & Poedts 2018; Narechania et al. 2021). To statistically evaluate the best fit, we used the Pearson correlation coefficient (cc), rmse error (rmse), and normalized difference of standard deviation of \( V_{\text{HUX}} \) and \( V_{\text{OBS}} \) (nsd). The best match was decided on the basis of a score (\( \Sigma \) in Equation (3)) giving equal weight to all three, with a lower \( \Sigma \) value signifying a better match:

\[
\Sigma = (1 - \text{cc})^2 + \left( \frac{\text{rmse}}{100} \right)^2 + \text{nsd}^2. \tag{3}
\]

We selected five CRs for comparison, near the solar minima region and in the absence of halo CMEs, to properly capture the features of ambient solar wind. Considering that the accuracy of the GONG magnetogram has degraded since 2013, especially in polar regions (Nikolic 2019), we focused more on the increasing phase of Solar Cycle 24. The optimal values of \( \beta \) for selected CRs, based on HUX, have been listed in Table 1, and variations are shown in Figure 5. Panel 5(a) shows the variability of the \( \Sigma \) value for all CRs. As \( \beta \) increases from 0.75 to 1.75, the change in \( \Sigma \) value is lesser for CR2077, CR2104, and CR2202 (decline of <0.3), whereas CR2053 and CR2053 show greater deviation (incline of >0.4). The optimal \( \beta \) value lies in the middle of the chosen range for CR2104 and CR2202; in contrast, it lies at the boundary for CR2053, CR2077, and CR2081. This means that for the last three CRs the real optimum value can be located outside the chosen range of \( \beta \). But at their optimum value, the slopes of their plots have become almost zero (Figure 5(d)). This indicates that no significant reduction in \( \Sigma \) value will occur with further change of \( \beta \), and therefore the chosen range is adequate.

In Figure 5, rmse has monotonically increased with \( \beta \) for CR2104 and CR2081, decreased for CR2053, and remained almost constant for CR2077 and CR2202. The Pearson cc became better with increased values of \( \beta \) for CR2053, CR2077, and CR2202, whereas the cc value decreased for CR2081 and CR2104. The normalized standard deviation (nsd) first increased and then decreased for CR2053, CR2077, and CR2202. And in the case of CR2081 (CR2104), the nsd value strictly increased (decreased) with \( \beta \).

There is no noticeable pattern among the CRs in the panels of Figure 5, but different optimum \( \beta \) values for different CRs emphasize the influence of the \( d \) parameter. A higher \( \beta \) value implies greater influence of \( d \) on the speed profile, as compared to its lower value. Therefore, it can be inferred that in the WSA relation (Equation (1)), dominance of \( d \) is greater in CR2053 (\( \beta = 1.75 \)) as compared to CR2081 (\( \beta = 0.75 \)).

As expected, Figure 6 demonstrates that even small variations in \( \beta \) have significant impacts on the speed profile, particularly at peaks, where the value of \( d \) is high. As the \( \beta \) value is increased from 0.75 to 1.25 and 1.75, the peak shifts upward, and its fluctuations in that region also increase. The same trend will continue until the threshold value is reached, and then no further change will happen, as the speed profile becomes independent of \( d \) (see Figure 4).

### 2.2. Submodel for Inner Heliosphere

The fundamental purpose of the MHD-based inner heliospheric model is to determine plasma properties in the inner heliosphere by taking the input from the coronal model. The veracity of this domain depends on accurate initial boundary conditions, which vastly depend on the speed profile derived from the WSA relation. More details have been prescribed in the following subsections.

#### 2.2.1. MHD Setup

The inner heliospheric model is based on the PLUTO code (Mignone et al. 2007), which is built on Godunov-type schemes to integrate a set of conservation laws using a finite-volume or finite-difference approach. In the current version of

![Figure 5](image-url) Plots showing the statistical results for variation of \( \beta \) from 0.75 to 1.75 in 20 equal steps, for five selected CRs. On the basis of the minimum score value, the optimum \( \beta \) value has been deduced. The chosen optimum for each CR has been marked with a cross, whose values have been mentioned in Table 1. All panels have a common plot legend, shown in panel (a).

| CR    | Optimal Value of \( \beta \) | cc   | rmse | nsd | \( \Sigma \) |
|-------|-----------------------------|------|------|-----|----------|
| 2053  | 1.75                        | 0.85 | 74.01| 0.04| 0.57     |
| 2077  | 1.75                        | 0.64 | 75.20| 0.14| 0.72     |
| 2081  | 0.75                        | 0.87 | 41.39| 0.03| 0.19     |
| 2104  | 1.0                         | 0.85 | 44.51| 0.09| 0.23     |
| 2202  | 1.3                         | 0.54 | 74.35| 0.02| 0.77     |

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The Astrophysical Journal Supplement Series, 262:23 (16pp), 2022 September

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SWASTi-SW, the ideal MHD module of PLUTO is used on a uniform static grid in spherical coordinates. The following set of conservative equations are solved using the finite-volume method:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0
\]

\[
\frac{\partial m}{\partial t} + \nabla \left\{ m \mathbf{v} - B \mathbf{B} + \left( p + \frac{B^2}{2} \right) \right\} = \rho g
\]

\[
\frac{\partial B}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) = 0
\]

\[
\frac{\partial E_i}{\partial t} + \nabla \cdot \left\{ \left( \frac{\rho v^2}{2} + \frac{\gamma p}{\gamma - 1} \right) \mathbf{v} + \mathbf{B} \times (\mathbf{v} \times \mathbf{B}) \right\} = m g,
\]

where \( \rho \) is mass density, \( v \) is velocity, \( m \) is momentum density \( (\rho v) \), \( B \) is magnetic field, \( p \) is isotropic thermal pressure, \( g \) is gravitational acceleration \( (-GM/r^2) \), \( E_i \) is total energy density, and \( \gamma \) (\( = 5/3 \)) is specific heat ratio of solar wind plasma. The above equations are solved in the Stonyhurst heliographic frame. The coordinates of this frame can be converted to the Heliocentric Earth Equatorial (HEEQ) frame by mere spherical to Cartesian coordinate transformation \( \text{Thompson 2006} \). To incorporate the solar rotation in this frame, the inner radial boundary (the whole spherical slice at \( R_{\text{in}} \)) is rotated with constant angular speed with respect to the computational grid. The rotational time period \( (\text{TP}) \) remains constant for a specific CR and can have values from 27.21 to 27.34 days \( \text{Thompson 2006} \), depending on the location of Earth in its orbit. For example, the value of TP for CR2053 (starting from 2007 February) is 27.34 days, whereas value of TP for CR2081 (starting from 2009 March) is 27.30 days. And the corresponding centrifugal and Coriolis terms have been neglected owing to their trifling share.

The MHD domain range goes from 0.1 to 2.1 au in radial, \(-60^\circ \) to \(60^\circ \) in latitudinal, and \(0^\circ \) to \(360^\circ \) in longitudinal direction, having \(150 \times 120 \times 360\) grid resolution, respectively. With the motivation to keep the computational time reasonable, we opted for simple numerical methods involved in a typical time step cycle in PLUTO. For each step we chose the RK2 time-stepping algorithm, second-order TVD linear reconstruction scheme, and HLLC Riemann solver. And to ensure the divergence-free condition, we selected Powell’s eight-wave formulation \( \text{Powell 1994} \).

### 2.2.2. Boundary Specification

The coronal domain provides the speed profile (radial component of \( V, V_r \)) for each flux tube, at the inner boundary of the MHD domain \( (R_{\text{in}}) \). For forecasting purposes, the default values of parameters in the adapted WSA relation, for the MHD run, are \( V_{\text{min}} = 250 \text{ km s}^{-1}, V_{\text{max}} = 650 \text{ km s}^{-1}, w = \text{median of } \Delta E_r, \text{ and } \beta = 1.25 \), but in this paper \( \beta \) values listed in Table 1 have been taken for assessment. Here the value of \( V_{\text{max}} \) is 75 \text{ km s}^{-1} less than the value that was used in HUX. A decreased value of \( V_{\text{in}} \) has been applied to compensate for the effect of additional acceleration in the MHD domain \( \text{McGregor et al. 2011} \). As the coronal domain does not include solar rotation, the speed profile is rotated in the longitudinal direction by angle \( \alpha \):

\[
\alpha = 5 + \left( \frac{2\pi}{\text{TP}} \right) \left( \frac{20.5 R_{\text{in}}}{(V_{\text{in}})_{\text{min}}} \right)
\]

where \((V_{\text{in}})_{\text{min}}\) is the minimum value of \( V_{\text{in}} \). The values of other plasma properties at \( R_{\text{in}} \) are derived from the following empirical relations:

\[
n = n_0 \left( \frac{V_{\text{max}}}{V_r} \right)^2
\]

\[
B_r = \text{sgn}(B_{\text{corona}}) B_0 \left( \frac{V_r}{V_{\text{max}}} \right)
\]

\[
B_\phi = -B_r \sin \theta \left( \frac{V_{\text{in}}}{V_r} \right),
\]

where \( n \) is plasma number density, \( n_0 = 300 \text{ cm}^{-3} \), \( B_r \) and \( B_\phi \) are radial and azimuthal components of \( B, B_0 = 300 \text{ nT} \), and \( V_{\text{in}} \) is rotating speed of the inner boundary corresponding to TP. Here \( n_0 \) and \( B_0 \) refer to number density and magnetic field values of fast solar wind, respectively. The thermal pressure \( p \) has been kept constant at \( R_{\text{in}} \) at 6.6 nPa. The meridional and azimuthal components of velocity \( (V_{\theta} \text{ and } V_{\phi}) \) are assumed to be zero at \( R_{\text{in}} \). The empirical relations (Equations (9), (10), and (11)) are similar to those used in Odstrcil (2003) and Poedts & Poedts (2018). The coronal models usually underestimate the heliospheric magnetic flux, i.e., a significant part of magnetic flux goes undiscovered \( \text{Linker et al. 2017} \). Therefore, implementing
an empirical relation, based on properties of fast wind and speed of that flux tube, sidesteps this problem.

Figure 7 exhibits the input of the MHD model for CR2081 at 0.1 au. Panels (a) and (b) are of $d$ and $f_\theta$ (in logarithmic scale), which are used to compute the solar wind speed (panel (d)) using the adapted WSA relation, and further, the speed profile is used to evaluate the radial magnetic field (panel (c)) using Equation (10). Though the latitudinal range of the MHD domain goes from $-60^\circ$ to $+60^\circ$, the quantities at 0.1 au are calculated for a wider range.

At the outer boundary, the radial direction is set to the outflow condition, i.e., zero gradient across the boundary, whereas latitudinal and longitudinal directions are reflective and periodic, respectively, on both sides of the computational domain. In the reflective boundary condition, the variables are symmetrized across the boundary.

It is worth mentioning that due to the usage of the above empirical relations, the only difference left between coupled PFSS+SCS and PFSS alone is the field-line tracing technique. SCS provides more realistic tracing by incorporating the nonzero current in the current sheet region, and as a result, the latitudinal value at $R_\text{in}$ differs from the pure radial (zero current) extrapolation, which is used in case of the PFSS-alone approach. Usually, this latitudinal difference is less than 1 for most of the field lines, and its effect can truly be noticed only when model resolution is better than 1. Therefore, for a lower-resolution setup, PFSS+SCS and PFSS alone will not show significant difference. In this work, we have used the PFSS-alone procedure by bypassing the SCS model.

### 3. Solar Wind Forecasting and Assessing Capabilities

The motivation of this work is to develop a solar wind forecasting model that could run on a personal workstation in reasonable computational time. The model setup was formulated accordingly and ran on a workstation having 48 cores, which computes the final result for the mentioned resolution in approximately 6.5–9.5 hr. To validate the model output, we introduce the initial results of the current version of SWASTi-SW for selected CRs. The chosen CR numbers (starting month) are CR2053 (2007 February), CR2077 (2008 November), CR2081 (2009 March), CR2104 (2010 November), and CR2202 (2018 March). The sample CRs are taken in a way to cover regions around the minima of the solar cycle. The first CR resides in the minima region of the descending phase of solar cycle 23, and the later three CRs belong to the ascending phase of solar cycle 24, starting from its minima, whereas the fifth CR corresponds to minima of descending phase.

The spatial domain of the MHD region goes up to 2.1 au, covering the region of Mercury, Venus, Earth, and Mars. A snapshot of the output is shown in Figure 8, where panels (a), (b), and (c) are of radial velocity in different planes and panels (d), (e), and (f) are plots of radial magnetic field, proton density, and proton temperature, respectively. Panels (c)–(f) are in the $\theta - \phi$ plane at 1 au, and density and temperature have been shown in logarithmic scale to display the structure clearly. A heliospheric current sheet, where the polarity of magnetic field changes, can be observed in the middle of panel (d). The field lines near the current sheet region originate from the edge of the coronal hole; therefore, solar wind speed must be low in this region. And slow solar wind has higher density, which in turn leads to lower thermal temperature. As expected, panels (c), (e), and (f) also have current sheet structure with lower values of speed and temperature but higher values of density near the heliospheric current sheet region.

To compare our model results with observations, we used per-hour averaged solar wind magnetic field and plasma data from the OMNIWeb database. We interpolated the model output from 360 data points to number of hours in CR (say, $N$) for comparability. The model output and performance analysis are in the following subsections.

#### 3.1. Plasma Properties at L1

Figure 9 shows plasma speed for all the selected CRs at L1, using GONG (all CRs) and HMI (one CR) magnetograms. In this figure, the results of our MHD model and HUX technique have been compared with OMNI 1 hr averaged data. Since the
The observed plasma speed is mainly radial, it has been compared with the radial velocity of the model. The x-axis is flipped Carrington longitude, where 0 and 360 signify the start and end time of CR, respectively. Technically, the Carrington longitude starts from 360° and ends at 0°; therefore, it has been flipped to keep the CR starting time and 0 as origin on the left side. The comparison with other plasma properties is in Figure 10, where, additionally, magnetic field magnitude, number density, and proton temperature are shown.

The speed profile output of SWASTi-SW for CR2053 has successfully captured the observed structure (cc = 0.81 and rmse = 80.87 km s⁻¹), which has two local sideward peaks and a global peak at the center in Figure 9. Though the positions of sideward peaks have matched well, the global peak seems to be slightly shifted to the right by a few hours.

In CR2077, the leftmost peak has bifurcated and become broader, but the positions of the rest of the structure show a decent match. A considerable difference in the slope of HUX and MHD profiles is visible around 210 Carrington longitude, where a physics-based result gives a better match with the observed value. As the HUX technique neglects the effects of the pressure gradient, the gradual increase in solar wind speed was not achieved, which was effectively produced in the MHD result. Considering the fact that HUX extrapolates in only one direction, latitudinal flow of plasma could also be playing a role.

The speed is higher in the middle region for CR2081, but the overall pattern is the same. The HUX result has a better match in this case, whereas in the case of CR2104, GONG magnetogram results are having a good match for both HUX (cc = 0.86) and MHD (cc = 0.84). They have accurately captured the whole structure except for a minor peak in the middle. But the HMI result for CR2104 MHD (cc = 0.57) is not matching that well; it has failed to reproduce the global maxima, near 240, accurately.

For CR2202, the same slope difference feature is visible around 240 as it was in CR2077 at 210. Again, the physics-based result is able to capture the observed form, whereas HUX is showing a very sharp peak at that position. An abrupt fall at the beginning of the profile can be noticed, as compared to the observed one. A possible reason could be the cyclic nature of the model input, which enforces the same value at the end and beginning of the cycle.

Figure 10 shows the plots of other plasma properties for CR2081. The magnetic field output and observation data have the same order of magnitude as it varies under 20 nT. The overall pattern is also showing the same trend. However, the

Figure 8. Snapshots of output of the inner heliospheric model. The results are for CR2081. Panels (a), (b), and (c) are the radial velocity plots, whereas panel (d) is plot of radial magnetic field (nT), panel (e) is of proton density (Np cm⁻³) in logarithmic scale, and panel (f) is of proton temperature (MK) in logarithmic scale. Panel (a) is in the r–f plane at Earth’s latitude location, panel (b) is in the r–θ plane at 0° longitude, and panels (c)–(f) are in the θ–f plane at 1 au. The blue circle at 1 au in panels (a) and (b) is the location of Earth at the starting of CR2081. The green, gray, and red circles in panel (a) denote Mercury, Venus, and Mars, respectively, whereas the orange circle at the center highlights the Sun. This figure is available as an animation. The real-time duration of the animation is 7 s. (An animation of this figure is available.)
1 hr averaged OMNI data have very rapid fluctuations, which is missing in the interpolated model output. On the other hand, the density plot is always higher than the observed one, indicating that the model is overestimating the plasma number density at L1, whereas the temperature plot’s peaks are always lower, implying that the model underestimates the proton temperature. The statistical details of other CRs are mentioned in Table 2.

In addition to the used value of $\gamma (= 5/3, \gamma_0)$, we have also shown the results for $\gamma = 1.50 (\gamma_1)$ and $\gamma = 4/3 (\gamma_2)$ in Figure 10. The profile of all three presented properties showed some changes, with temperature varying the most. With the decrease in $\gamma$ value, the proton temperature increased significantly. $\gamma_1$ and $\gamma_2$ profiles gave a better match for the peak around 60$^\circ$ as compared to $\gamma_0$, but the rest of their profile gave high mean error values, especially $\gamma_2$. In the density plot,
all three showed similar linear correlation, but the mean error of the $\gamma_0$ profile was higher at peaks. For magnetic field, all three profiles have equivalent linear correlation and rmse. However, the $\gamma_0$ profile shows a better match than $\gamma_1$ and $\gamma_2$ at the 60° peak. Furthermore, the accuracy of solar wind speed profile also reduced with the $\gamma$ value ($\text{rmse for } \gamma_0 = 84.99 \text{ km s}^{-1}$, $\gamma_1 = 86.12 \text{ km s}^{-1}$, $\gamma_2 = 87.10 \text{ km s}^{-1}$). Therefore, a slight decrease in $\gamma$ value, from 5/3, might give a better match for proton temperature and density, but the magnetic field and plasma speed accuracy might decrease.

3.2. Solar Wind Interaction Region

Apart from determining the plasma properties in the inner heliosphere, SWASTi-SW can also be used to study the high-speed solar wind streams (HSSs) and SIRs. Additionally, the model can also mimic the observations of in situ instruments of the upcoming Aditya-L1 mission. For example, Figure 11 shows the schematic diagram of SWIS, which is a subsystem of the Aditya Solarwind Particle EXperiment (ASPEX). The three-dimensional physics-based model allows us to assess the characteristic of SIRs at L1, which can be used as a template for directional-dependent data acquired by such in situ payloads (see Section 4 for details).

Statistical studies (e.g., Tsurutani et al. 2006; Alves et al. 2006; Zhang et al. 2008) have shown that SIRs/HSSs are chiefly responsible for weak to moderate geomagnetic storms. SIR is produced when HSS interacts with its preceding slower solar wind stream. This interaction causes the formation of compressed plasma density and interplanetary magnetic field (IMF) at the leading edge of the rising section in the speed profile.

Belcher & Davis (1971) classified this interaction into four regions S, S', F', and F, i.e., the unperturbed slow wind, accelerating slow wind, decelerating fast wind, and ambient fast wind regions, respectively. The compressed S' and F' regions form the SIR with enhanced plasma density and magnetic field magnitude. We observed the same kind of structure formation in predicted plasma properties at L1. Figure 12(a) shows the SIR occurring in the first quarter of the CR2081 simulation. Panels (a1), (a2), and (a3) show the rise in radial velocity, magnetic field magnitude, and density in the interaction region. Panels (a4) and (a5) display the fluctuation in the azimuthal component of velocity and flow angle ($\tan^{-1}\left(\frac{v_y}{v_x}\right)$), where $x$ and $y$ are in HEEQ) during the interaction region. A similar pattern was also predicted for the transverse component of the velocity vector in Belcher & Davis (1971, Figure 17). Furthermore, we observed an additional peculiar...
Table 2
Statistical Results of Comparison of Model Output with the OMNI Data at L1

| CR_MAP     | Statistical Parameter | HUX Speed (km s\(^{-1}\)) | HUX Speed (km s\(^{-1}\)) | | MHD | | |
|------------|-----------------------|-----------------------------|-----------------------------| | | | |
|            |                       | cc                          | rmse                        | std\(_\text{model}\)  | std\(_\text{obs}\)  | 119.46 | 2.03 | 4.51 | 0.10 |
|            |                       | 0.85                        | 0.81                        | 0.46                    | 0.40 | 0.04 | 57.0 |
| 2053_GONG  |                       | 74.01                       | 80.87                       | 4.16                    | 20.83 | 0.09 | 93.33 | 2.30 | 5.17 | 0.06 |
|            |                       | 123.97                      | 135.07                      | 4.46                    | 19.93 | 0.10 |
| 2077_GONG  |                       | 0.64                        | 0.73                        | 0.20                    | 0.39 | 0.40 |
|            |                       | 75.21                       | 63.58                       | 2.57                    | 14.74 | 0.07 |
|            |                       | 80.12                       | 71.63                       | 1.29                    | 12.41 | 0.06 |
| 2081_GONG  |                       | 69.75                       | 100.03                      | 2.02                    | 8.12 | 0.04 |
|            |                       | 67.69                       | 85.59                       | 1.48                    | 13.27 | 0.05 |
| 2104_GONG  |                       | 75.48                       | 85.59                       | 1.48                    | 13.27 | 0.05 |
|            |                       | 67.69                       | 85.59                       | 1.48                    | 13.27 | 0.05 |
| 2104_HMI   |                       | 0.86                        | 0.84                        | 0.21                    | 0.32 | 0.31 |
|            |                       | 43.58                       | 47.81                       | 2.58                    | 14.33 | 0.06 |
|            |                       | 75.48                       | 85.59                       | 1.48                    | 13.27 | 0.05 |
| 2104_HMI   |                       | 68.90                       | 73.14                       | 2.45                    | 16.42 | 0.08 |
|            |                       | 63.63                       | 63.29                       | 1.82                    | 14.11 | 0.06 |
| 2104_HMI   |                       | 68.90                       | 73.14                       | 2.45                    | 16.42 | 0.08 |
|            |                       | 63.63                       | 63.29                       | 1.82                    | 14.11 | 0.06 |
| 2202_GONG  |                       | 0.54                        | 0.68                        | 0.40                    | 0.34 | 0.25 |
|            |                       | 74.35                       | 61.86                       | 2.85                    | 13.44 | 0.06 |
|            |                       | 74.37                       | 78.63                       | 3.08                    | 12.25 | 0.04 |
| 2202_GONG  |                       | 0.54                        | 0.68                        | 0.40                    | 0.34 | 0.25 |
|            |                       | 74.35                       | 61.86                       | 2.85                    | 13.44 | 0.06 |
|            |                       | 74.37                       | 78.63                       | 3.08                    | 12.25 | 0.04 |
|            |                       | 0.54                        | 0.68                        | 0.40 | 0.34 | 0.25 |
|            |                       | 74.35 | 61.86 | 2.85 | 13.44 | 0.06 |
| 2202_GONG  |                       | 0.54 | 0.68 | 0.40 | 0.34 | 0.25 |
|            |                       | 74.35 | 61.86 | 2.85 | 13.44 | 0.06 |
|            |                       | 74.37 | 78.63 | 3.08 | 12.25 | 0.04 |

Note. Here std\(_\text{model}\) is the standard deviation of the model output at 1 au and std\(_\text{obs}\) is the standard deviation of the observed OMNI data at L1.

trait for plasma flux in the meridional and azimuthal directions, which is discussed in detail in Section 4.

4. ASPEX: Aditya-L1

The upcoming Indian solar mission Aditya-L1 has seven payloads: four remote sensing and three in situ instruments. ASPEX is one of the three in situ payloads and has multidirectional measurement capabilities. SWIS and STEPS are two independent subsystems of ASPEX, which, in turn, have two and six units, respectively. The primary scientific objective of SWIS is to study the solar wind plasma particles, whereas that of STEPS is to investigate the suprathermal particles and SEPs (Goyal et al. 2018).

The two independent units of SWIS, Top Hat 1 (THA-1) and Top Hat 2 (THA-2), will measure the particle flux in an energy range of 100 eV–20 keV. THA-1 has a field of view (FOV) of 360° along the ecliptic plane and will be capable of differentiating the major solar wind ion species (proton and alpha particles). On the other hand, THA-2 will measure total particle flux with an FOV of 360° in the plane perpendicular to the ecliptic plane. Each THA has an electrostatic analyzer (ESA) section that selects the incoming ions based on their energies. In THA-1, there is an additional magnetic mass analyzer (MMA) section that deflects the major ions as per their masses to eventually get detected by a microchannel plate. The position information of the incident charges is derived from the in-house-developed resistive anode encoder (RAE). It consists of a number of metallic tracks printed on a PCB material. The position information is derived based on the voltage division across the resistive chains and readout at the end (A1–A2, B1–B2, C1–C2, D1–D2). It is to be noted that RAE of THA-1 consists of four quadrants, and each resistive chain in a quadrant consists of four sectors that amount to an angular resolution of 22.5° (16 sectors). This is shown in Figure 11(a). In addition to the fact that THA-2 is mounted perpendicular to THA-1, there is one more fundamental difference between the THA-1 and THA-2 units. THA-2 does not have any MMA section, and hence it is not designed to separate protons and alpha particles. In the absence of the MMA section, the particles fall on an annular region on RAE that is around the mean radius of the ESA. Therefore, RAE in THA-2 consists of a thin annular strip of a single resistive chain and readouts at the end of the strip. In addition to these differences, THA-2 also has 32 sectors that result in an angular resolution of 11.25°. The schematic of the RAE of THA-2 is shown in Figure 11(b). Therefore, once deployed at L1, SWIS will continuously measure the proton and alpha particles individually in radial and azimuthal directions and integrated flux in the meridional direction.

In this work, we have used our simulation results to synthesize the measurements of SWIS by forming three computational planes (namely, A, B, and C), each in the radial, meridional, and azimuthal direction. Each plane is made up of nine grid cells and is at a distance of \(dr \sim 2.8 R_e\), \(d\theta\) (1), and \(d\phi\) (1) from the L1 grid cell, in their respective unit vector directions. Figure 11(c) displays the computational planes that cover the FOV of SWIS, and the L1 grid cell is represented by Earth’s logo. The values at nine grid cells are used to find the
averaged values of quantities at L1, which are plotted in Figure 12 (b).

We used the abovementioned averaging technique to imitate the observation of SWIS, with the aim of showing how its multidirectional measurement capability could lead to more accurate detection of SIRs. For demonstration purposes, we chose a well-defined SIR in the first quarter of CR2081. Figures 12(b1) and (b2) are of averaged radial and azimuthal components of velocity, and they are very much similar to their value at the L1 grid cell, implying that the employed technique is satisfactory. Figures 12(b3), (b4), and (b5) are of proton flux density in radial, meridional, and azimuthal directions, respectively. In all the three flux plots, there is significant change in the $S'$ and $F'$ (shaded) regions. The radial flow has increased, meridional flow has changed its direction, and azimuthal flow is fluctuating rapidly in the shaded $S'$ and $F'$ regions. Similar features were also observed for interaction regions at 120 and 300 of CR2053, 60 of CR2077, and 240 of CR2104. This collective feature occurring in the proton flux profile in three directions, especially the fluctuations in azimuthal flow and meridional flow, can be called the characteristic feature of SIRs. The observation of such multidirectional features can be used to detect SIR events at L1, along with the rise in plasma density, IMF magnitude, and fluctuations in longitudinal direction. The combined observation of the three specified features will provide a better SIR detection functionality.

5. Summary and Discussion

In this work, we presented an indigenous physics-based solar wind forecasting model for the inner heliosphere that uses an adapted semiempirical approach for the initial boundary condition. This 3D model has been developed with an intention to run on a personal workstation in reasonable computational time with adequate accuracy. On average, the coronal domain takes around 2 hr and the inner heliospheric domain takes around 6.5 hr for one complete CR run on a 48-core processor. This computational time is for the resolution and setup mentioned in Section 2. To reduce this computational time, users can opt for a lower angular resolution of 2. However, due to a lack of sampling in the longitudinal and latitudinal directions, features of SIR (as depicted in Figure 12) would be rather diffused and their identification would be troublesome. Therefore, when SIR assessment is not the objective, the user can opt for a lower angular resolution.

In this study, two types of magnetograms have been used to validate the results with observation, GONG and HMI. Being the only observational input, accuracy of the magnetogram directly affects the veracity of model prediction. Both GONG and HMI measure the LOS component and provide the radial flux in the azimuthal direction. Along with the onboard magnetometer (MAG), Aditya-L1 will have the ability to measure the rise in plasma density, IMF magnitude, and fluctuations in longitudinal direction. The combined observation of the three specified features will provide a better SIR detection functionality.
component of magnetic field on the solar surface. They do so by dividing the observed magnitude by the cosine of the angle from the disk center and assuming that the fields are purely radial at the photosphere. But this approximation is sensible only in those regions where the field is not strong enough to resist the fluid forces, like for quiet and weak active regions and not for strong active regions. Therefore, an inevitable discrepancy is always present in the model’s input, which ultimately gets reflected in final results.

In SWASTi-SW, the initial boundary condition of the MHD domain is based on an adapted version of the original WSA relation (Arge et al. 2003). We generalized the empirical

**Figure 12.** Plots showing the features of plasma properties at L1 corresponding to SIR for CR2081. Panel (a) represents the computed plasma properties at the L1 location, whereas panel (b) represents the mass-averaged properties at L1. The shaded region (S’ and F) shows the SIR where in the S’ region (between red and green dotted vertical lines) solar wind is getting accelerated and in the F region (between green and red dotted vertical lines) plasma is getting decelerated. $V_r$ and $V_\phi$ are plasma velocity in radial and azimuthal direction in km s$^{-1}$. $|B|$ and $N$ are IMF magnitude (nT) and proton density ($N_p$ cc$^{-1}$). Panel (a5) shows the variation of flow angle in degree. $(V_r)_{avg}$ and $(V_\phi)_{avg}$ are averaged values of $V_r$ and $V_\phi$ (km s$^{-1}$). $(\rho V_r)_{avg}$, $(\rho V_\phi)_{avg}$, and $(\rho V_\phi)_{avg}$ are averaged proton flux ($N_p$ cm$^{-3}$ s$^{-1}$) in radial, meridional, and azimuthal directions. The x-axis, longitude, is flipped Carrington longitude, as in Figures 9 and 10.
this approach would be helpful in the inner heliospheric domain, especially in latitudinal and longitudinal directions.

An effort to optimize the value of one other independent parameter using the HUX algorithm was also demonstrated. Though this method uses observational data and cannot be directly used for forecasting purposes, a long-term study using this approach would be helpful in finding the optimal set of values of independent parameters. A possible future work would be to use such an extensive data set from long-term studies to automatize the choice of free parameters for any given CR period.

The results from comparison suggest that SWASTI-SW is capable of forecasting the ambient solar wind properties at L1, especially that the correlation of plasma speed is high (up to $c_{\text{s}} = 0.84$). The model does overestimate (underestimate) the value of plasma density (temperature), and this is something that should be explored in future works. We showcased that a reduced value of specific heat ratio ($\gamma$) leads to additional heating, but it also decreases the density and magnetic field intensity. Therefore, a spatially varying relation of $\gamma$ can be a reasonable alternative for a better match. Another rational approach could be the introduction of anisotropic pressure terms in an MHD equation to incorporate more insightful physics.

We demonstrated the directional-dependent features (e.g., velocity, proton flux, flow angle) of SIRs using our model and also presented a synthetic measurement to mimic the observations of the SWIS. At this point, we again reiterate that SWIS-THA-1 does not have very good latitudinal coverage but does have exceptional azimuthal coverage. On the other hand, SWIS-THA-2 has exceptional latitudinal coverage but limited azimuthal coverage. Therefore, by combining THA-1 and THA-2 measurements, one can pick up the signatures of SIRs in three dimensions. Additionally, Rout et al. (2017) showed that for geoeffectiveness, CIR azimuthal flow angle is mostly within $6^\circ$. The advantage here is that ASPEX can capture the signatures of the arrival of SIRs/CIRs at the L1 point at all azimuthal and elevation angles—some of these will turn out to be geoeffective, and some will not. In addition, the STEPS subsystem that covers six directions can detect the energetic particles arriving from the SIR/CIR shock fronts. Therefore, SWIS and STEPS together, along with the modeling outputs, can be very important for SIR/CIR investigations and can pave the way for the forecasting of their arrival. This framework will therefore complement the upcoming ISRO mission Aditya-L1. Specifically, SWASTI-SW will compliment the in situ measurements of solar wind properties by ASPEX and MAG.

We acknowledge the support provided by IIT Indore to carry out this work. P.M. would like to acknowledge the financial support provided by the Prime Minister’s Research Fellowship. B.V. and D.C. would like to kindly acknowledge the support from the ISRO RESPOND grant No. ISRO/RES/2/436/21-22. The work of D.C. is supported by the Department of Space, Government of India. We would also like to place on record the untiring efforts and contributions of the whole ASPEX team at PRL in the realization of the payload. The support and inputs from the Space Application Center (SAC), Ahmedabad, various ISRO Centers, splinter groups, review committees, and Aditya Science Working Group are duly acknowledged. The guidance and support from the Director, PRL, toward the ASPEX project are invaluable.

The used GONG and HMI synoptic magnetogram maps can be freely obtained from https://gong.nso.edu/data/magmap/crmag.html and http://jsoc.stanford.edu/HMI/Magnetograms.html, respectively. The OMNI data are taken from the Goddard Space Flight Center, accessible at https://spdf.gsfc.nasa.gov/pub/data/omni/. The PFSSPY python package used in this work for PFSS modeling is available at https://pffsry.readthedocs.io/en/stable/. The PLUTO code used for MHD simulation can be downloaded free of charge from http://plutocode.ph.unito.it/.

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