Improving Solar Wind Predictions Using Multi-Satellite In Situ Observations

DEPARTMENT OF SPACE SCIENCE
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

Dinesha V. Hegde[1,2], Tae K. Kim[2], Nikolai V. Pogorelov[1,2], Charles N. Arge[3], Shaela I. Jones[3,4]

[1] Department of Space Science, The University of Alabama in Huntsville, Huntsville, AL 35899 USA, [2] Center for Space Plasma and Aeronomic Research (CSPAR), The University of Alabama in Huntsville, Huntsville, AL 35899 USA, [3]NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA, [4]Catholic University of America, Washington, DC 20064, USA

Introduction

- ★ The knowledge of the ambient solar wind (SW) is of great importance for the correct description of coronal mass ejections (CMEs) propagating towards Earth. CMEs, on the other hand, are responsible for acceleration and transport of solar energetic particles (SEPs).
- ★ Accurate prediction of CME arrivals and of the magnetic field they carry is required for space weather (SWx) forecasts. Understanding the physical processes in the ambient SW plasma is therefore crucial for SWx forecasting.
- ★ Parker Solar Probe (PSP) (*Fox et al., 2016)* , which was launched on August 12, 2018, provides us with a unique set of in situ SW measurements at distances as close as the Sun's critical surface and below. This could help us in the validation of solar corona and inner heliospheric numerical models.
- ★ In addition to that, Solar Orbiter (SolO) (Müller et al., 2013) and STEREO-A are enabling us to study the SW using multi-satellite in-situ observations along with PSP.
- ★ We simulate the time dependent 3D global heliosphere using an empirically driven MHD model developed within the frameworks of the Multi-Scale Fluid-Kinetic Simulation Suite (MS-FLUKSS) (*Pogorelov et al., 2014)* using the photospheric magnetograms as input.
- ★ We compare our inner heliospheric SW simulations with multi-point in situ measurements along the PSP, SolO and Stereo-A trajectories as well as at Earth using the OMNI database during the PSP Encounter 8, where we have the near-radial alignment of satellites.

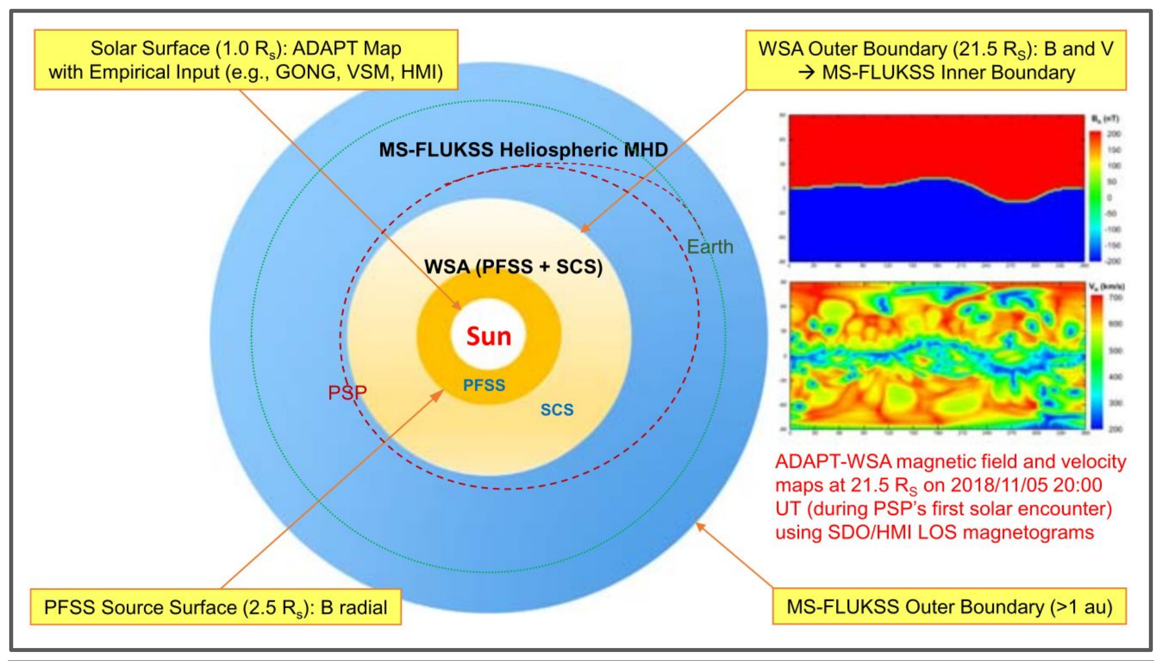


Fig-1: Diagram showing the time-dependent space weather model used in this study (Kim et al., 2020). The PSP and Earth trajectories are also shown (not to scale).

Methodology

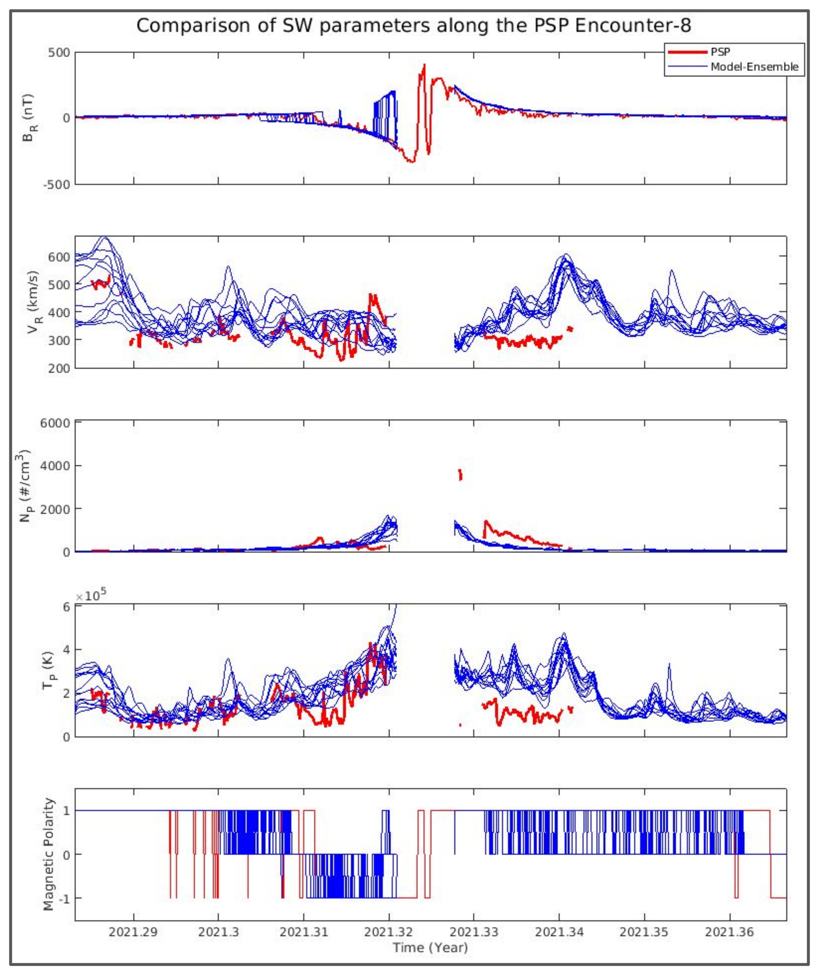
Our Space Weather Model: ADAPT/WSA/MS-FLUKSS

- ★ We use the Air Force Data Assimilative Photospheric flux Transport (ADAPT) (Arge et al., 2013) flux-transport model to construct B- maps using data assimilation technique, starting with the solar photospheric magnetic field (B) observation from SDO/HMI.
- ★ The boundary conditions for the inner heliospheric model are then designed using the traditional operational ADAPT-driven Wang–Sheeley—Arge (WSA) coronal model (Arge et al., 2003, 2004). It uses the Potential Field Source Surface (PFSS) model (Schatten et al., 1969) to extrapolate B from the photosphere to a source surface, ideally 2.5R_sun, and then to the outer boundary at 21.5R_sun using the Schatten's current sheet (SCS) model (Schatten, 1971).
- ★ We use Multi-Scale Fluid-Kinetic Simulation Suite (MS-FLUKSS), a suite of parallel numerical codes developed to model partially ionized plasma using adaptive mesh refinement (AMR) strategies, to simulate time-dependent 3D MHD solutions of the SW at any point in the inner heliosphere above the WSA outer boundary (Pogorelov et al., 2014).
- ★ We evaluate the performance of our space weather model and rank the ensemble of predictions based on available boundary conditions using the Model Prediction Metric (Model-PM) score and mean-square-error (MSE) analysis. Model PM assigns a score to each prediction based on the polarity of the magnetic field (P) and the velocity of the solar wind (V).

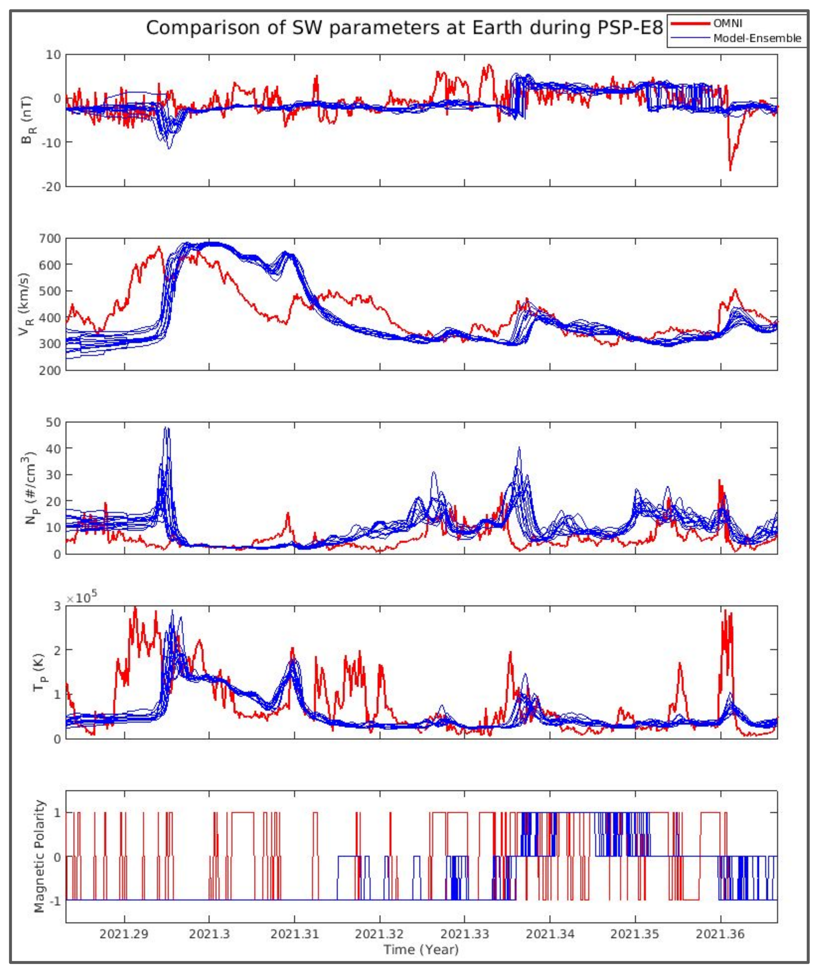
Note: The more accurate the forecast, the higher the MPM score. Formula —----->

$$MPM(t) = \frac{\frac{1}{N}\sum_{i=1}^{N}[1-\frac{1}{2}|P_{model}(t_i)-P_{obs}(t_i)|]}{\sqrt{\frac{1}{N}\sum_{i=1}^{N}[(V_{model}(t_i)-V_{obs}(t_i))^2]}}$$

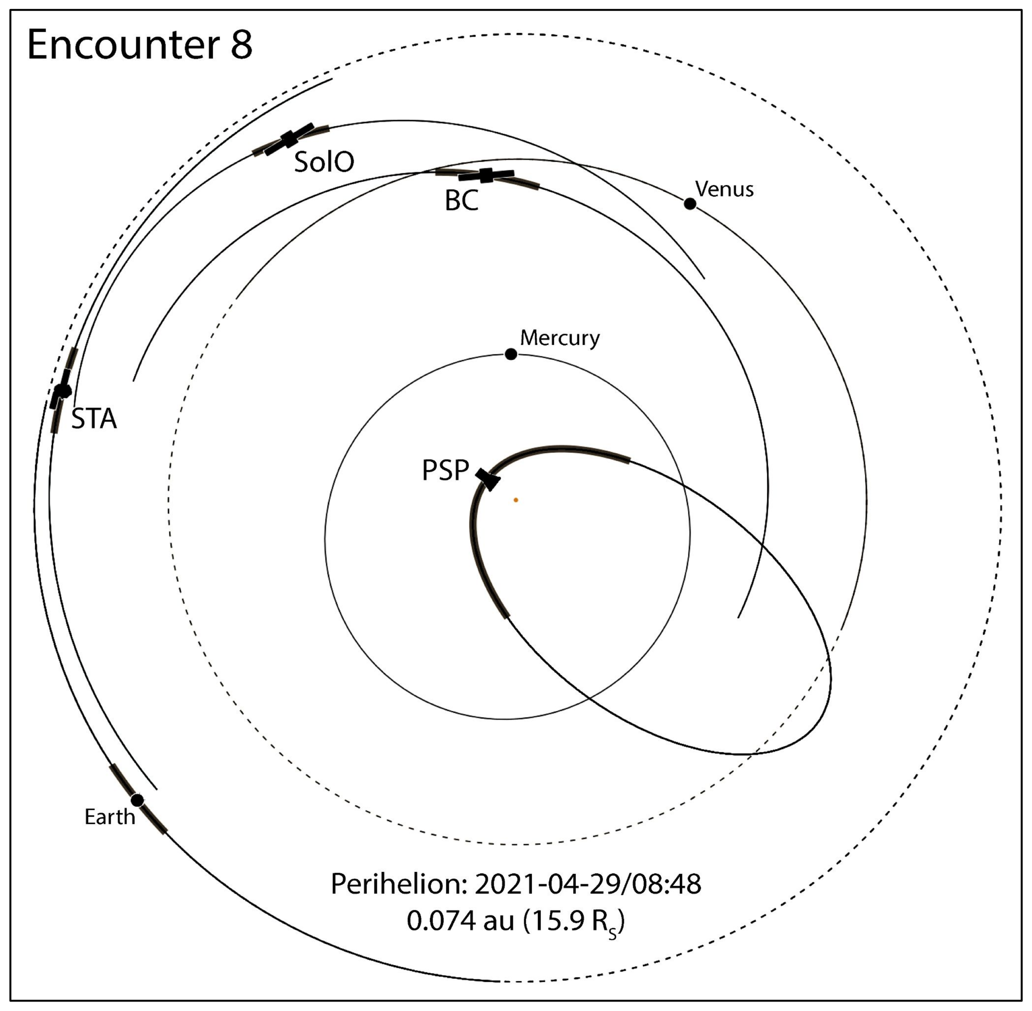
Parker Solar Probe



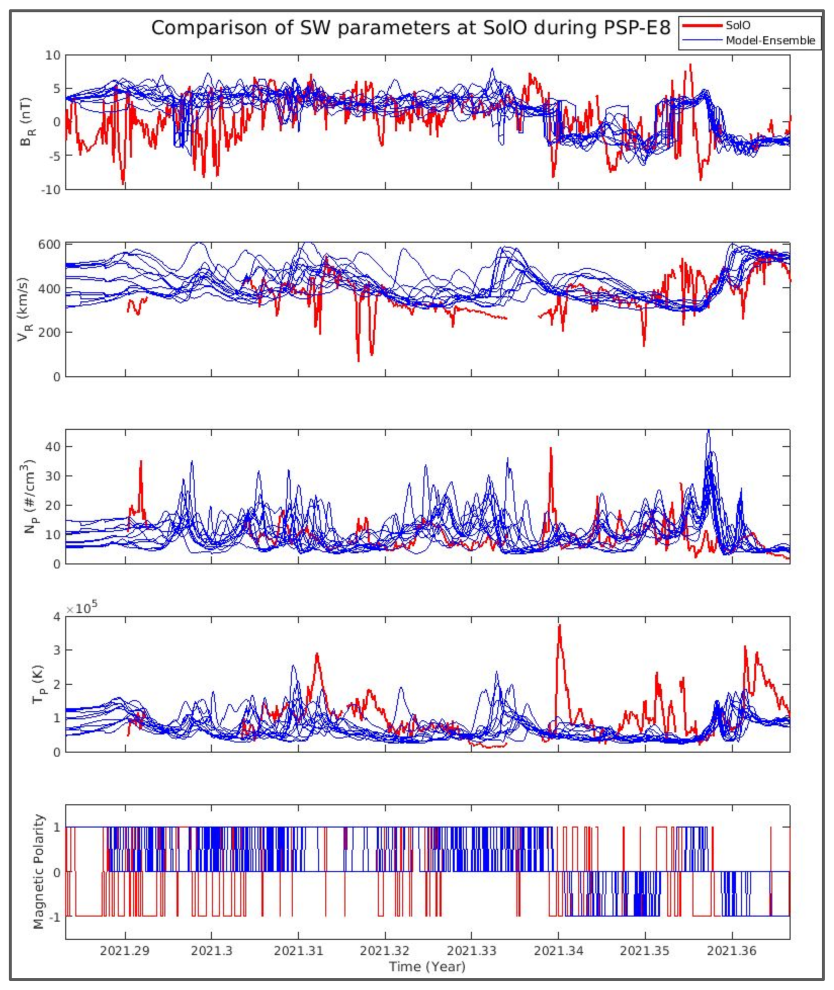
Earth



Results



Solar Orbiter



Stereo-A

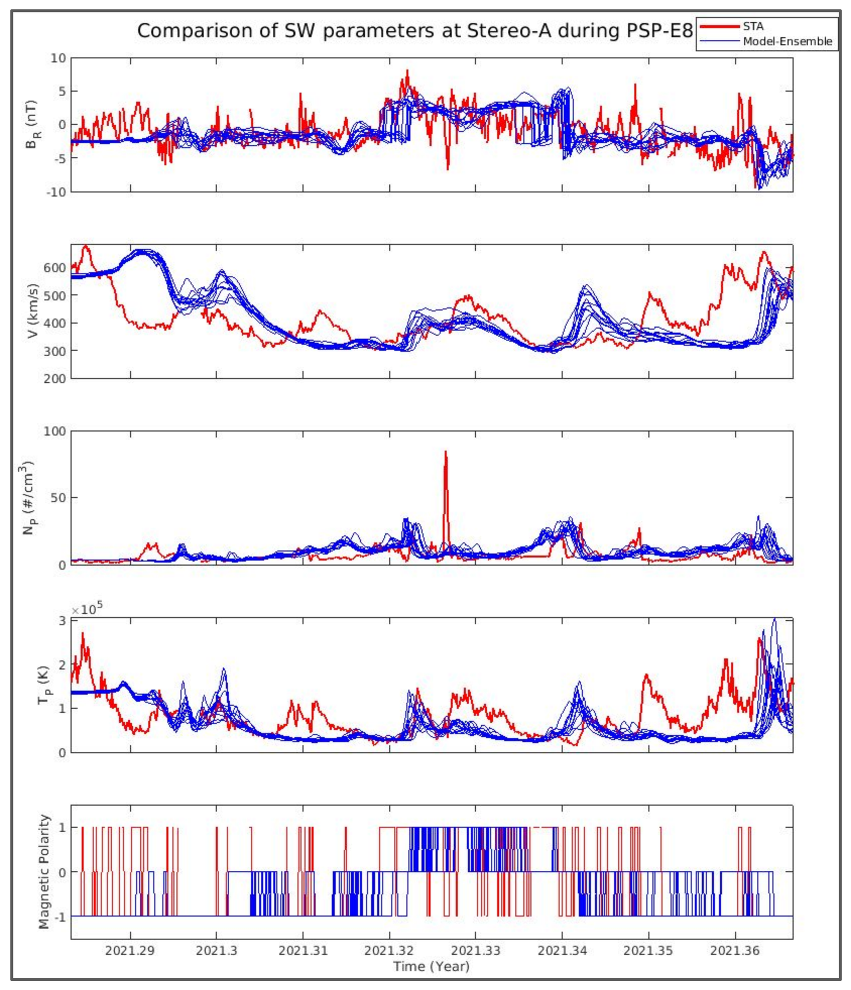
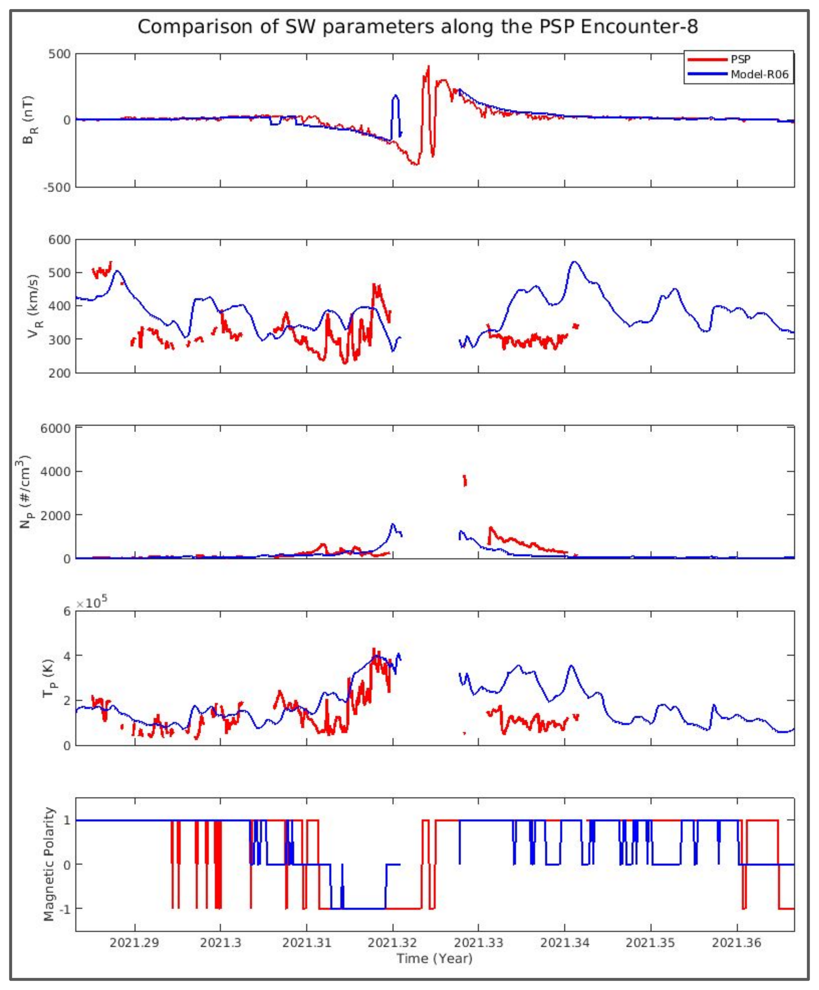
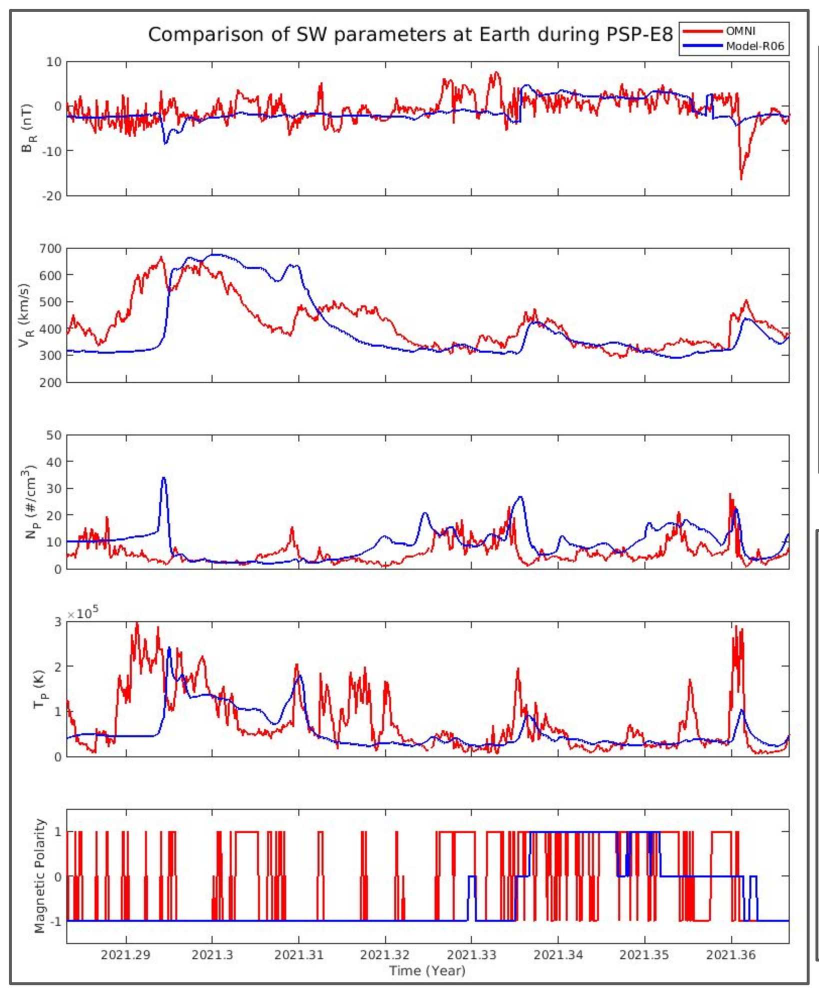
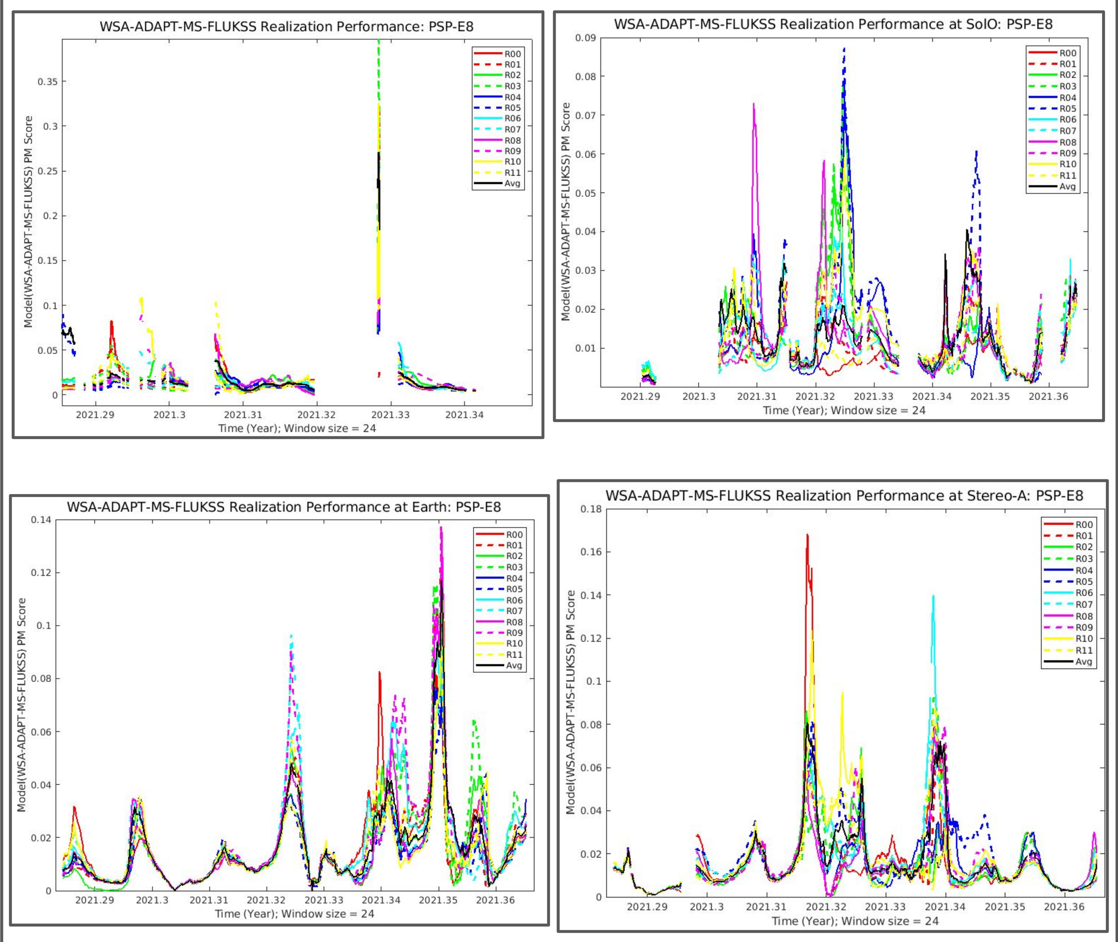


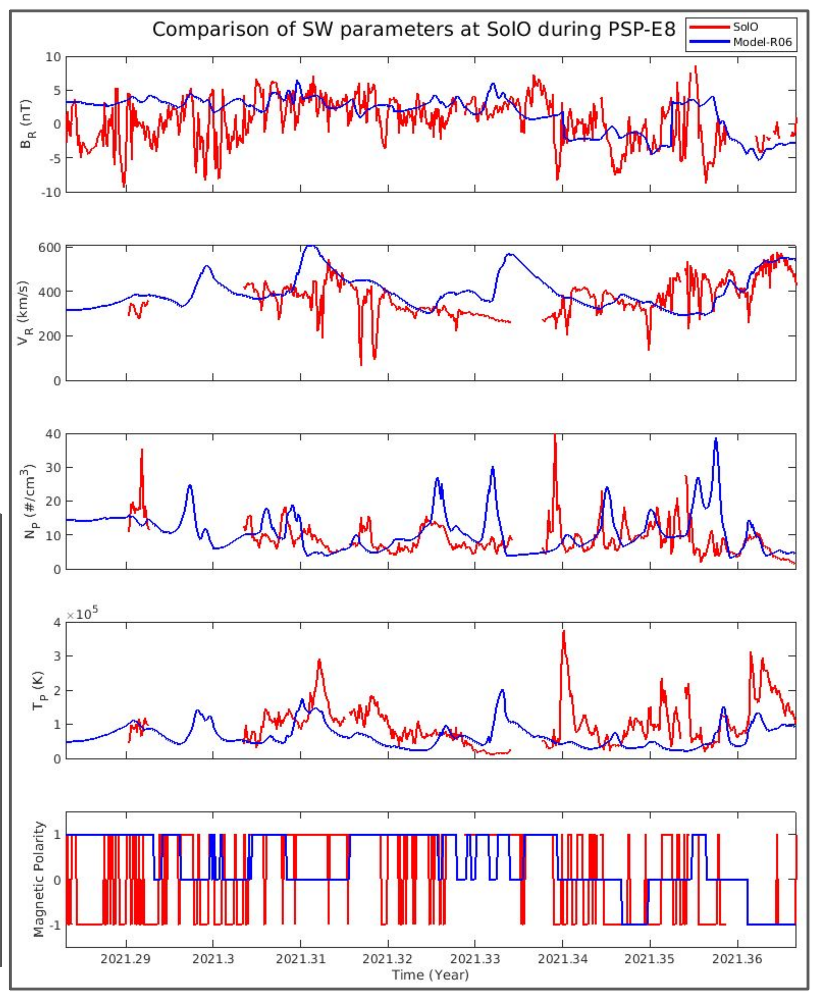
Fig-2: Radial components of magnetic field (nT) and solar wind velocity (km/s), proton density (cm^−3), temperature (K), and magnetic polarity for **all** the realizations at PSP, Earth **(Left panels)**, SolO, and Stereo-A **(Right panels)** respectively. Model results are shown in blue while observations are in red. **Middle Panel:** Map of PSP Encounter-8 showing the relative trajectories of Earth, SolO, Stereo-A and other satellites. We can see very small longitudinal differences (near -radial alignment) among PSP, STA, SolO & Earth.





Model Performance





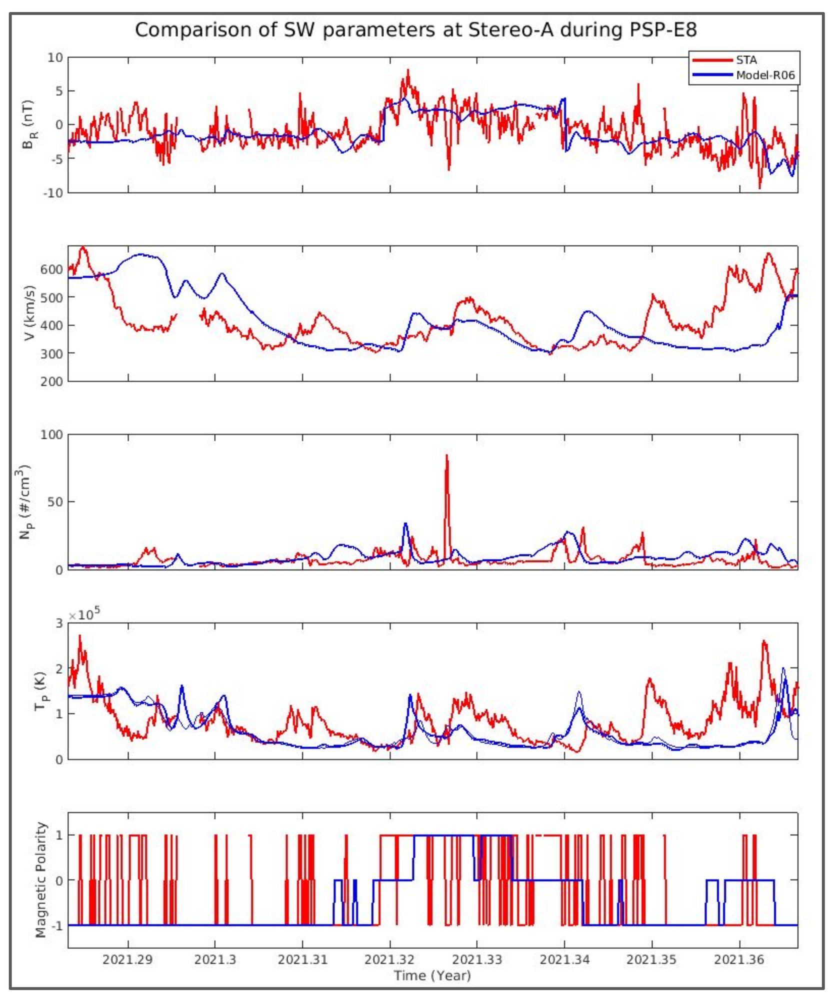


Fig-3: Radial components of magnetic field (nT) and solar wind velocity (km/s), proton density (cm^−3), temperature (K), and magnetic polarity for the **best** realization **(R06)** at PSP, Earth **(Left panels)**, SolO, and Stereo-A **(Right panels)** respectively. Model results are shown in blue while observations are in red. **Middle Panel:** Plots showing the model performance metric scores and ranking of all realizations and average of them at PSP (top left) , Earth (bottom left), SolO (top right), and Stereo-A (bottom right). Based on these score, we give more weightage to the performance of all realizations at Earth compared to others since the magnetic field observations are done near Earth (Eg. SDO/HMI).

Discussion

- ★ The comparison of the simulation results from our space weather model ensemble with the simultaneous Parker Solar Probe, OMNI (at Earth), Solar Orbiter and Stereo-A in-situ observations (fig-2) during 8th PSP encounter (PSP within 0.25 AU Heliocentric distance) helps us to validate our model very near to the solar atmosphere.
- ★ Due to the near-radial alignment of PSP, SolO, Stereo-A and Earth during the outbound leg of PSP encounter-8, this is a great opportunity to know the performance of our ensemble of model solution.
- ★ The gaps in the PSP simulation findings fig-2 & 3 are due to our simulation domain (our Inner Heliospheric model begins at 21.5 R sun), when PSP was less than 21.5 Rs.
- ★ MPM scores and MSE for all available WSA/ADAPT realizations are calculated to quantify the uncertainty in the prediction of SW parameters. We can rank the realizations using these scores.Due to the large data gaps in the plasma parameters of PSP/SPC, it is hard to calculate the the prediction metric (MPM) consistently.
- ★ Using the MPM scores it has been observed that uncertainties of the predictions during different periods of time and at different locations changes significantly. Ex: Best realization at PSP, Earth, SolO & Stereo-A are different. However, one can choose the best ensemble member based on weighted error analysis.
- ★ Most of the discrepancies in the simulation are possibly due to the inner heliospheric boundary conditions from the ADAPT/WSA maps. It is difficult to predict the SW emerging from coronal holes and in reality, just a few degrees of difference in the SW source region lead to large differences (100s Km/s) in speeds.
- ★ Comparison of our simulation results with multiple inner heliospheric mission data at various heliocentric distances and time periods of the solar cycle could provide new insights into solar wind acceleration. We believe that in the future, using multi-satellite (PSP, SolO & Stereo-A) constrained boundary conditions would improve the space weather simulation results significantly.

References

- ★ Arge, C. N., Henney, C. J., Hernandez, I. G., Toussaint, W. A., Koller, J., & Godinez, H. C. (2013), in AIP Conf. Series, Vol. 1539, Solar Wind 13, ed. G. P. Zank, et al., 11
- ★ Arge, C. N., Luhmann, J. G., Odstrcil, D., Schrijver, C. J., & Li, Y. (2004), J. Atmosph & Sol-Ter Physics, 66, 1295
- ★ Arge, C. N., Odstrcil, D., Pizzo, V. J., & Mayer, L. R. (2003), in AIP Conf. Proc. 679: Solar Wind Ten, 190
- ★ Fox, N. J., and 13 colleagues (2016), Space Sci. Rev.204, 7
- ★ Kim, T. K., and 22 colleagues (2020), Astrophys. J.Suppl.246, 40
- ★ Pogorelov, N., Borovikov, S., Heerikhuisen, J., Kim, T., Kryukov, I., Zank, G. 2014, XSEDE 2014 Proc., 22
- ★ Schatten, K. H., Wilcox, J. M., & Ness, N. F. (1969), Solar Phys., 6, 442
- ★ Schatten, K. H. (1971),, Cosmic Electrodynamics, 2, 232
- ★ Müller, D., Marsden, R. G., St. Cyr, O. C., Gilbert, H. R. 2013, Solar Phys., 285, 25

Acknowledgment

We acknowledge the NASA PSP Mission and the FIELDS and SWEAP teams led by S. D. Bale and J. Kasper, respectively, for use of data. This work is partly supported by the PSP Mission through the UAH SAO agreement SV4 84017. TKK and DVH acknowledge support from the AFOSR grant FA9550-19-1-0027. DVH acknowledges the support from the NASA FINESST grant 20-HELIO20-0021. This work utilizes data produced collaboratively between the Air Force Research Laboratory (AFRL) and the National Solar Observatory. The ADAPT model development is supported by AFRL. The authors acknowledge use of the SDO/HMI data from the Joint Science Operations Center (http ://jsoc.stanford.edu/) and Supercomputer time allocations were provided on SGI Electra and Pleiades by NASA High End Computing Program awards SMD-18-56966303 and SMD-20-92772410, and also on TACC Stampede 2 and SDSC Comet by NSF XSEDE project MCA07S033. This work was supported, in part, by NSF grant 2028154 “SWQU: Improving Space Weather Predictions with Data-Driven Models of the Solar Atmosphere and Inner Heliosphere.”

SHINE 2022, Honolulu, HI, June 27 to July 1, 2022