EGU21-12726: Large-scale Structure and Turbulence Transport in the Young Solar Wind – Comparison of Parker Solar Probe Observations with a Global 3D Reynolds-averaged MHD Model

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Abstract: Simulation results from a global magnetohydrodynamic model of the solar corona and the solar wind are compared with Parker Solar Probe's (PSP) observations during its first five orbits. The fully three-dimensional model (Usmanov et al., 2018, ApJ, 865, 25) is based on Reynolds-averaged mean-flow equations coupled with turbulence transport equations. The model accounts for effects of electron heat conduction, Coulomb collisions, Reynolds stresses, and heating of protons and electrons via nonlinear turbulent cascade. Turbulence transport equations for turbulence energy, cross helicity, and correlation length are solved concurrently with the mean-flow equations. We specify boundary conditions at the coronal base using solar synoptic magnetograms and calculate plasma, magnetic field, and turbulence parameters along the PSP trajectory. We also accumulate data from all orbits considered, to obtain the trends observed as a function of heliocentric distance. Comparison of simulation results with PSP data show general agreement. Finally, we generate synthetic fluctuations constrained by the local rms turbulence amplitude given by the model and compare properties of this synthetic turbulence with PSP observations.

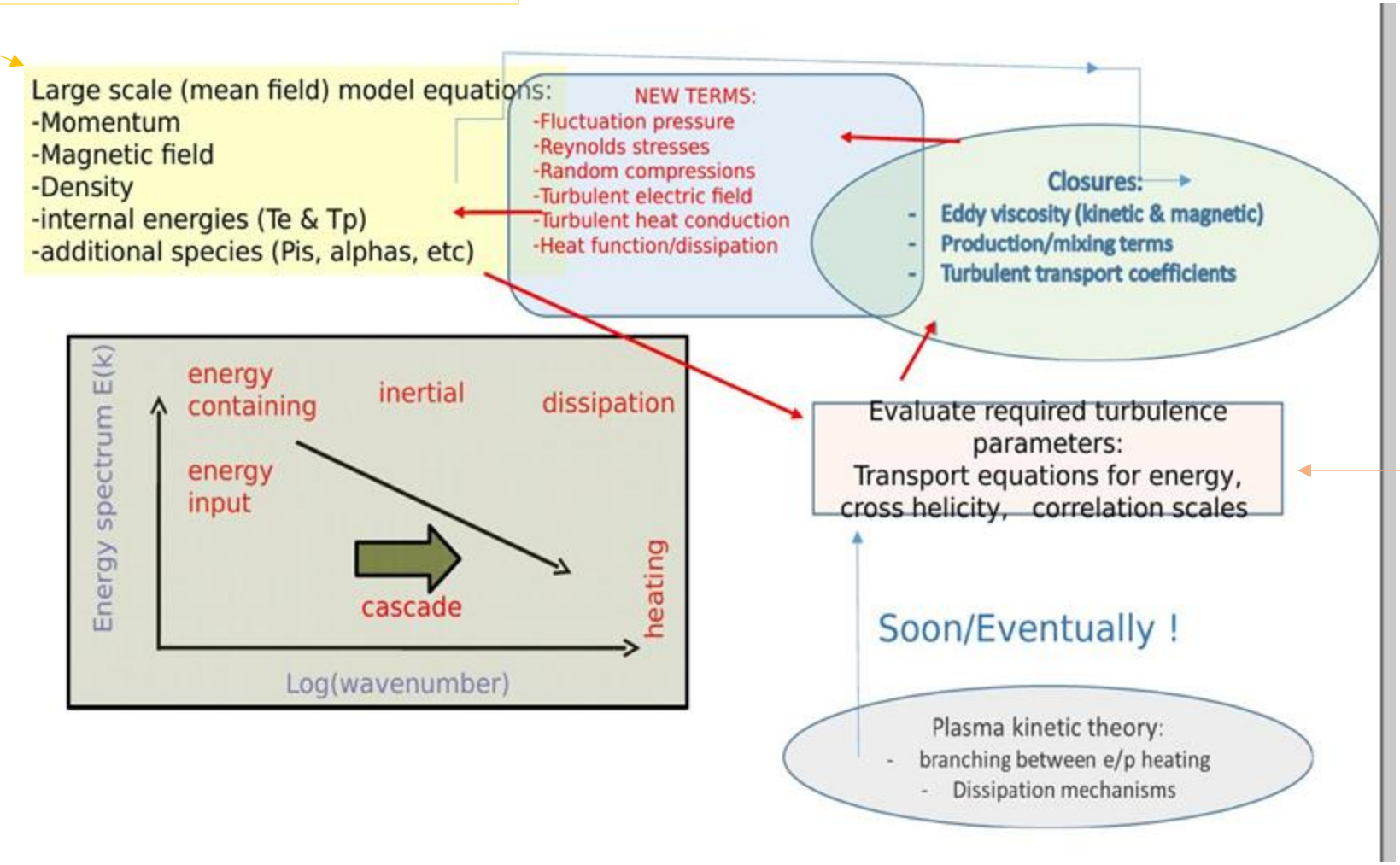
Introduction and Motivation – Turbulence in Global Solar Wind Simulations

- Solar wind is known to be turbulent, with structure and fluctuations across scales
- Turbulent cascade can provide a mechanism for coronal heating, and acceleration and heating of the solar wind
- Fluctuations can influence several physical processes in interplanetary space, including transport of SEPs
- Not computationally feasible to resolve fluctuations and turbulence cascade in a global simulation of solar wind
- We use a model based on Reynolds-averaging to obtain 3D solutions for both mean flow and statistical turbulence properties
- The results are compared with data aggregated from the first five Parker Solar Probe (PSP) orbits, which span heliocentric distances from 28 to 200 solar radii

Global simulation with turbulence modeling – Schematic of Reynolds-Averaging Approach

Reynolds decomposition splits fields (ã) into mean (a) and fluctuation (a'; arbitrary amplitude): $\tilde{a} = a + a'$

Explicitly resolve large-scale/mean flow



Describe fluctuations statistically

Two-Fluid Reynolds-averaged MHD with Turbulence Transport

- Average 2-fluid MHD equations to obtain mean-flow equations.
- Turbulence transport equations obtained by subtracting mean-flow eqns. from full eqns., and averaging.

mean flow

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

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot \left[\rho \mathbf{v}\mathbf{u} - \frac{1}{4\pi}\mathbf{B}\mathbf{B} + \left(P_S + P_E + \frac{B^2}{8\pi} + \frac{\langle B'^2 \rangle}{8\pi} \right) \mathbf{I} + \boldsymbol{\mathcal{R}} \right] = -\rho \left(\frac{GM_\odot}{r^2} + \boldsymbol{\Omega} \times \mathbf{u} \right)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B} + \varepsilon_m \sqrt{4\pi\rho})$$

$$\frac{\partial P_S}{\partial t} + (\mathbf{v} \cdot \nabla) P_S + \gamma P_S \nabla \cdot \mathbf{u} + (\gamma - 1) \frac{P_S - P_E}{\tau_{SE}} = f_p Q_T$$

$$\frac{\partial P_E}{\partial t} + (\mathbf{v} \cdot \nabla) P_E + \gamma P_E \nabla \cdot \mathbf{u} + (\gamma - 1) \left[\frac{P_E - P_S}{\tau_{SE}} + \nabla \cdot \mathbf{q}_H \right] = (1 - f_p) Q_T$$

turbulence

$$\frac{\partial Z^2}{\partial t} + (\mathbf{v} \cdot \nabla) Z^2 + \frac{(1 - \sigma_D) Z^2}{2} \nabla \cdot \mathbf{u} + \frac{2}{\rho} \boldsymbol{\mathcal{R}} : \nabla \mathbf{u} + 2\boldsymbol{\varepsilon}_m \cdot (\nabla \times \mathbf{u}) - (\mathbf{V}_A \cdot \nabla)(Z^2 \sigma_c) + Z^2 \sigma_c \nabla \cdot \mathbf{V}_A = -\frac{\alpha f^+(\sigma_c) Z^3}{\lambda}$$

$$\frac{\partial (Z^2 \sigma_c)}{\partial t} + (\mathbf{v} \cdot \nabla)(Z^2 \sigma_c) + \frac{Z^2 \sigma_c}{2} \nabla \cdot \mathbf{u} + \frac{2}{\rho} \boldsymbol{\mathcal{R}} : \nabla \mathbf{V}_A + 2\boldsymbol{\varepsilon}_m \cdot (\nabla \times \mathbf{u}) - (\mathbf{V}_A \cdot \nabla) Z^2 + (1 - \sigma_D) Z^2 \nabla \cdot \mathbf{V}_A = -\frac{\alpha f^-(\sigma_c) Z^3}{\lambda}$$

$$\frac{\partial \lambda}{\partial t} + (\mathbf{v} \cdot \nabla) \lambda = \beta f^+(\sigma_c) Z$$

- $Z^2 = \langle v'^2 + b'^2 \rangle$ is (twice the incompressible yurbulent energy per unit mass
- $\sigma_c = \dfrac{2\langle \mathbf{v}' \cdot \mathbf{b}' \rangle}{\langle v'^2 + b'^2 \rangle}$ is the normalized cross helicity
- λ is the similarity (correlation) length scale

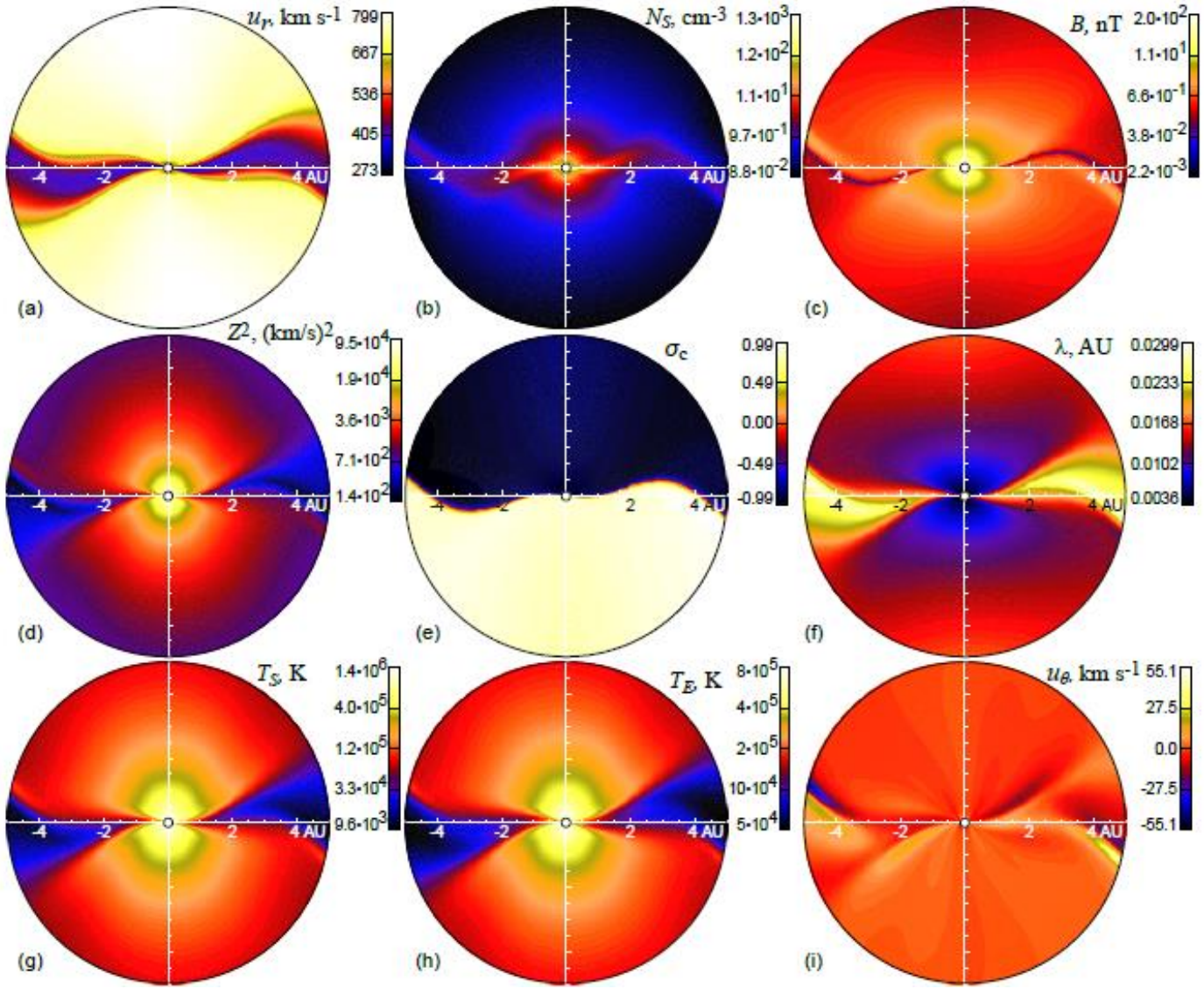
Turbulence modeling assumptions –

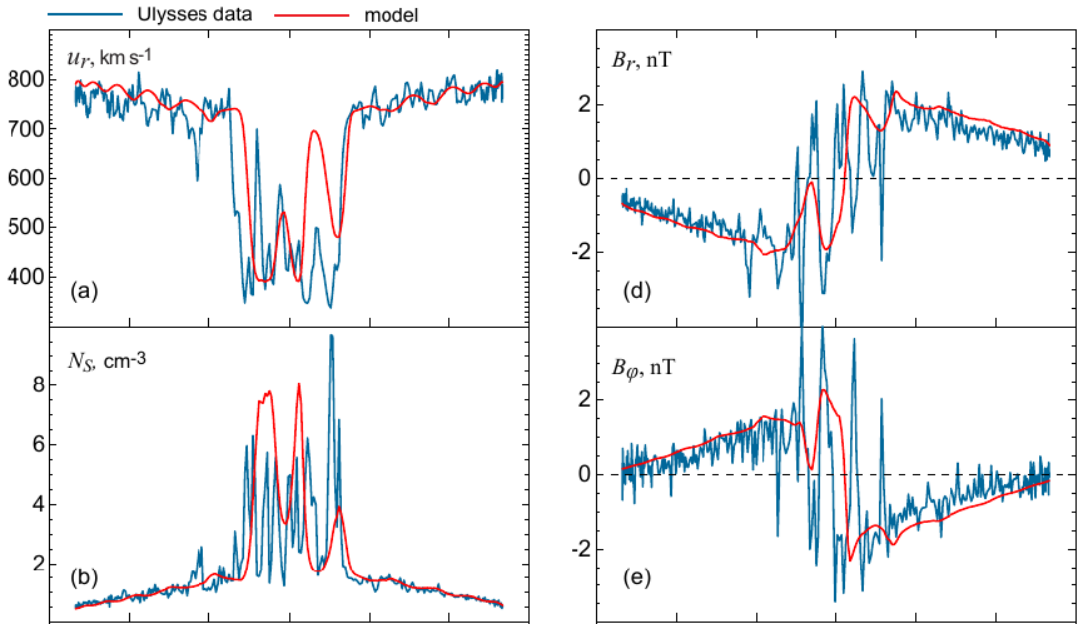
- Incompressible and transverse fluctuations
- Turbulent stresses modeled in terms of large-scale gradients (shear)
- NL terms modeled dimensionally (von Karman similarity)

- Physically and empirically motivated ICs and BCs
- Magnetogram-based or dipolar source magnetic field
- Numerical domain from coronal base to few AU

See Usmanov et al., 2018 for more details

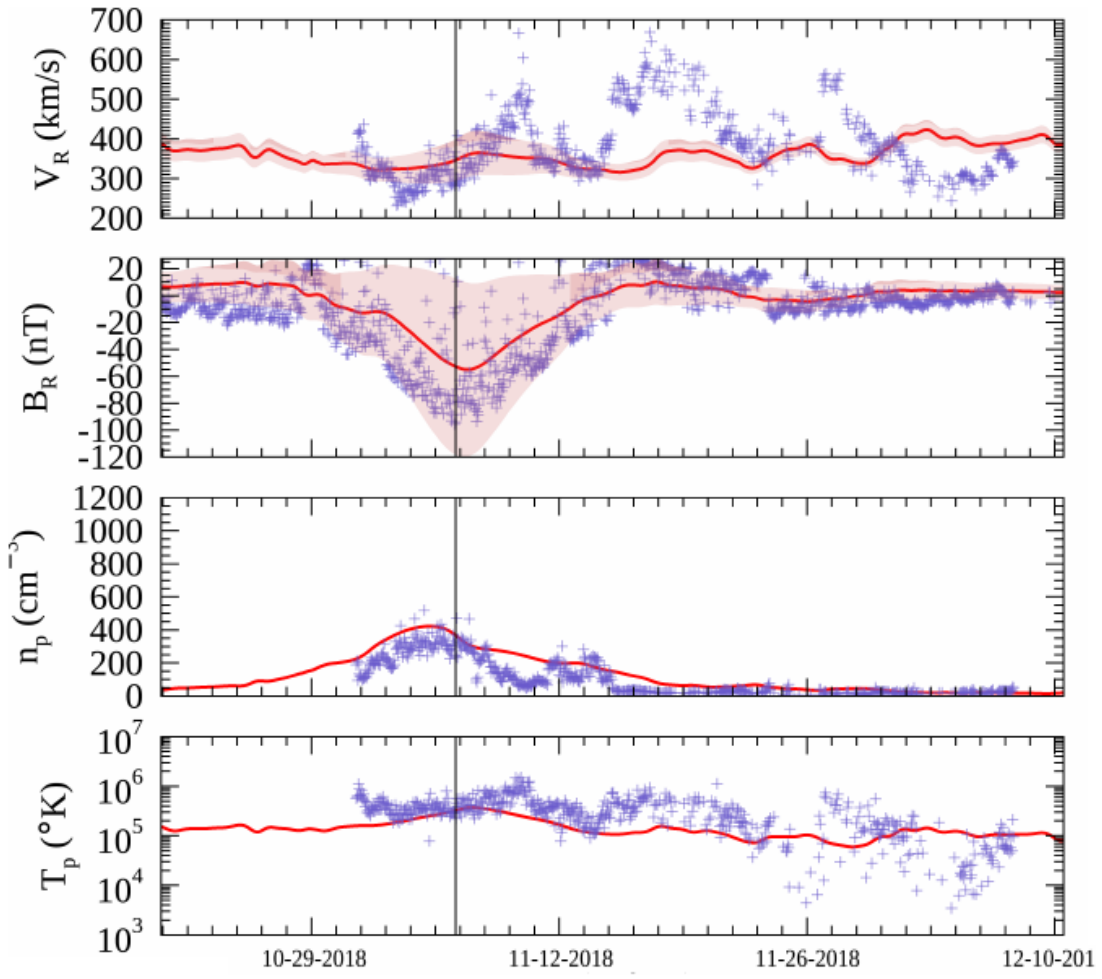
Sample Results – Meridional planes (30 Rs to 5 AU) and Comparison with Ulysses Data





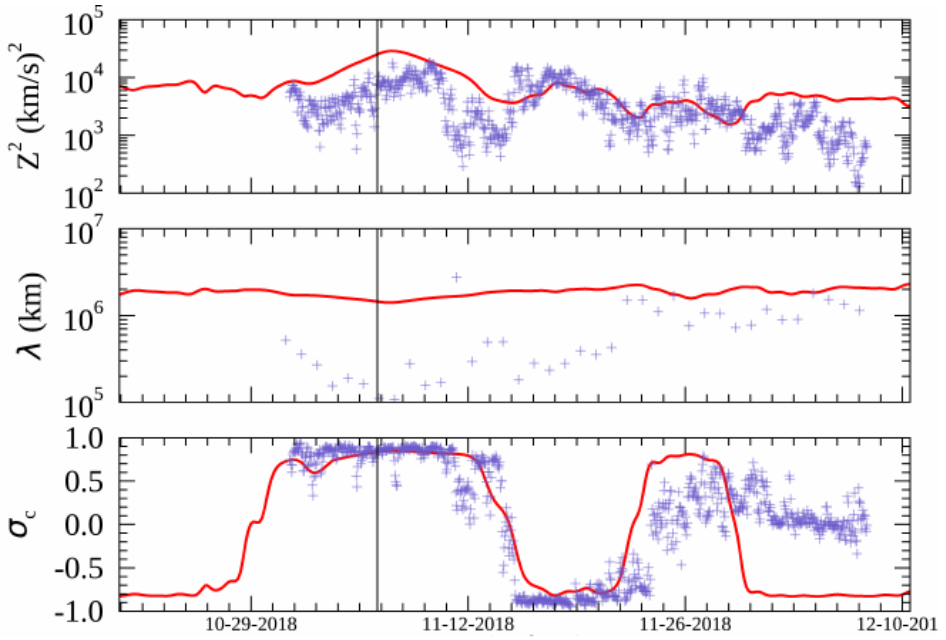
Usmanov et al., 2018

Comparison of model using Nov 2018 magnetogram with PSP O1 data

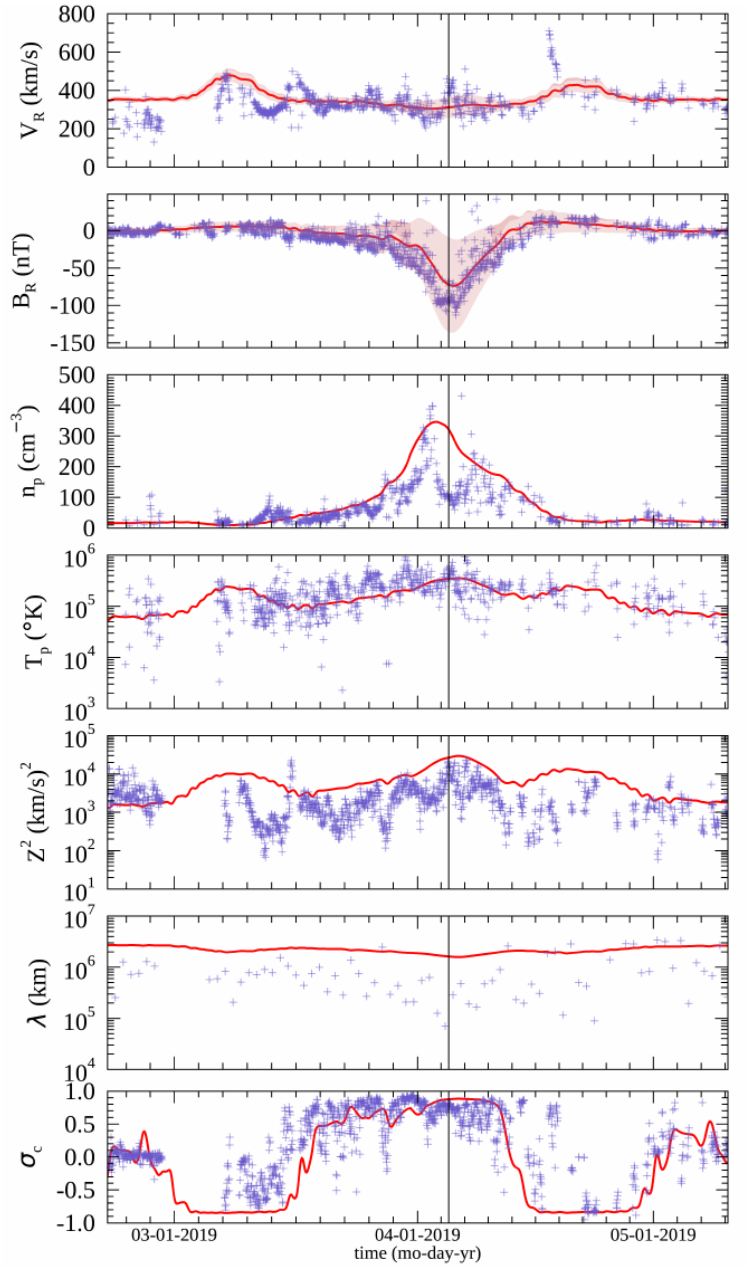


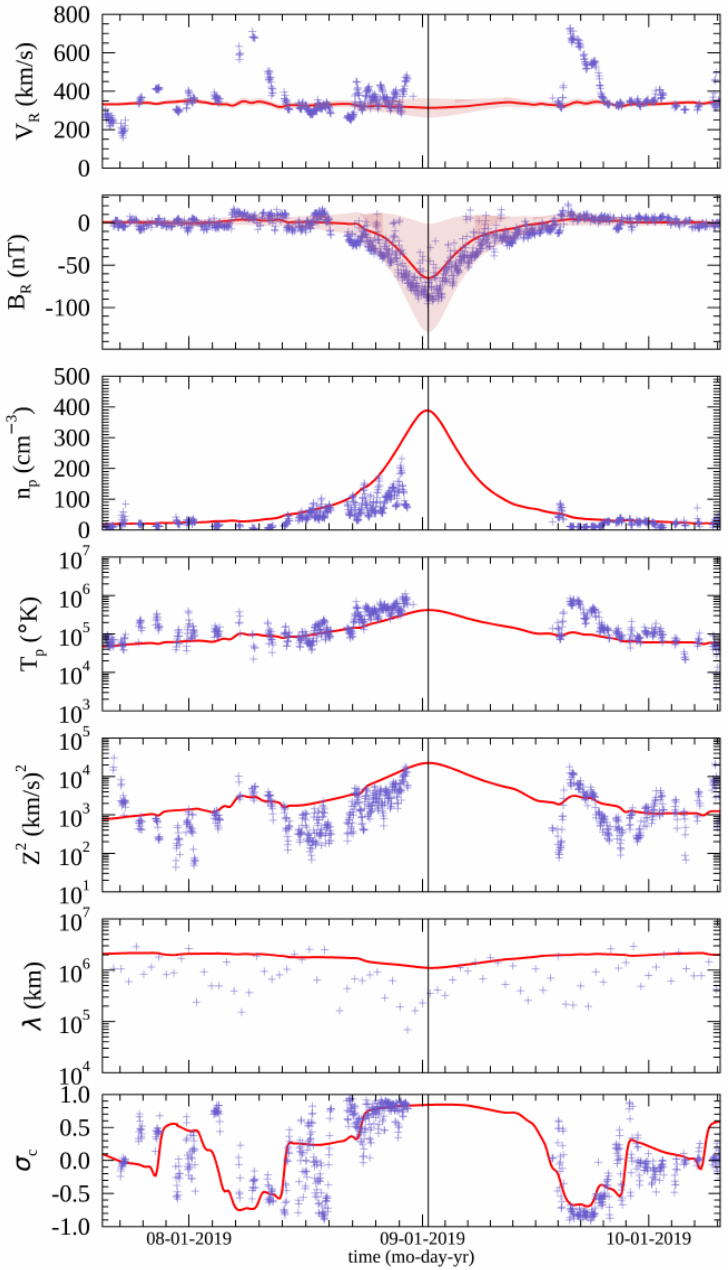
- Comparison of time series for O1. Top: Bulk flow parameters Right: Turbulence parameters.
- Symbols show hourly averages of PSP data; red curves show model results; shaded regions in VR and BR panels shows +/- turbulence amplitude from model

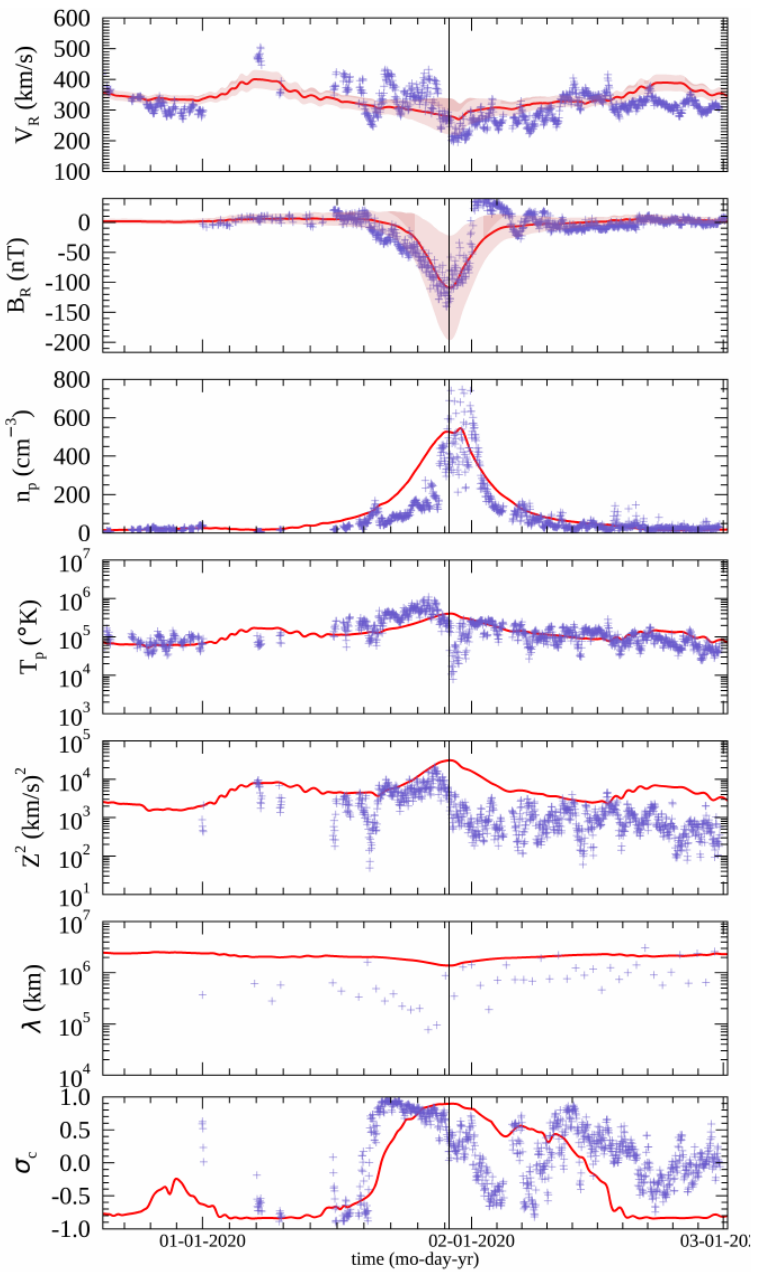
- FIELDS/MAG and SWEAP/SPC data are resampled to 1-sec cadence
- Fluctuations are computed using a rolling average over a 2-hour window
- Autocorrelations are computed using the Blackman-Tukey method (Matthaeus et al. 1982) over 1-day intervals. Computed correlation times are converted to lengths using the Taylor hypothesis (e.g., Chen et al. 2020)



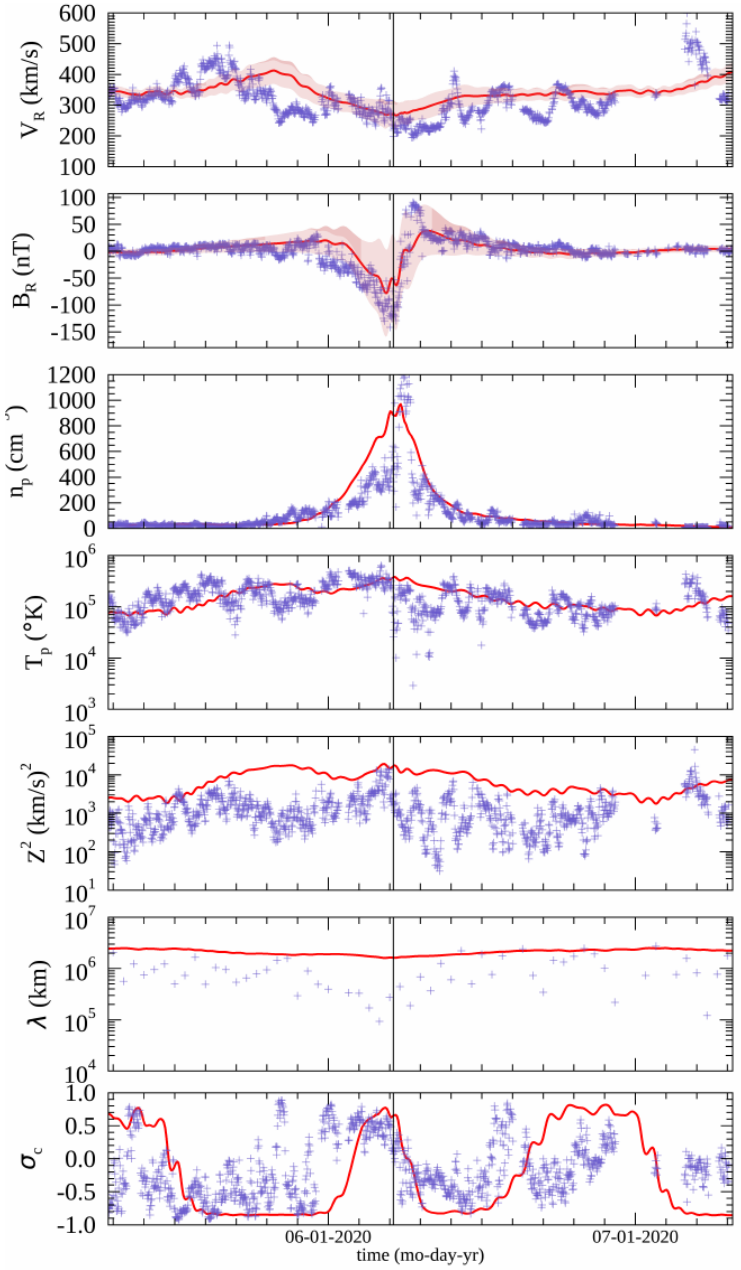
Comparisons of model with PSP Orbits 2, 3, and 4







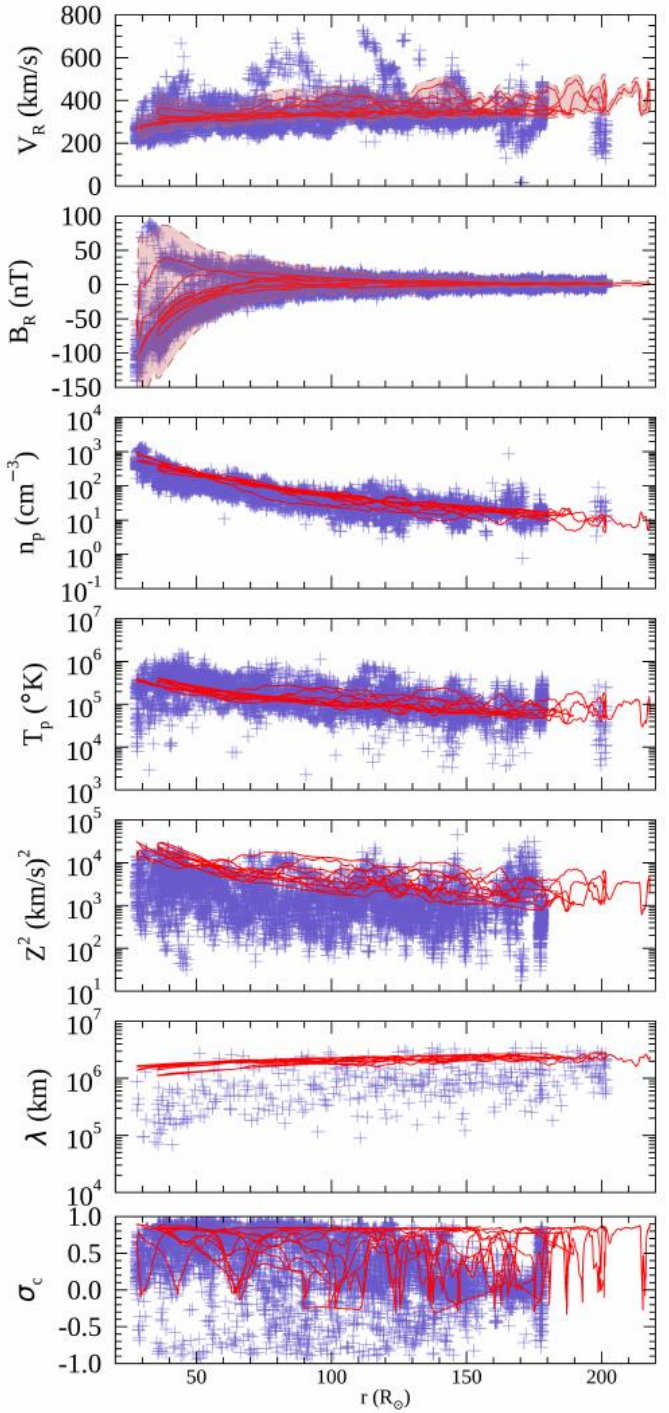
Comparisons of model with PSP Orbit 5

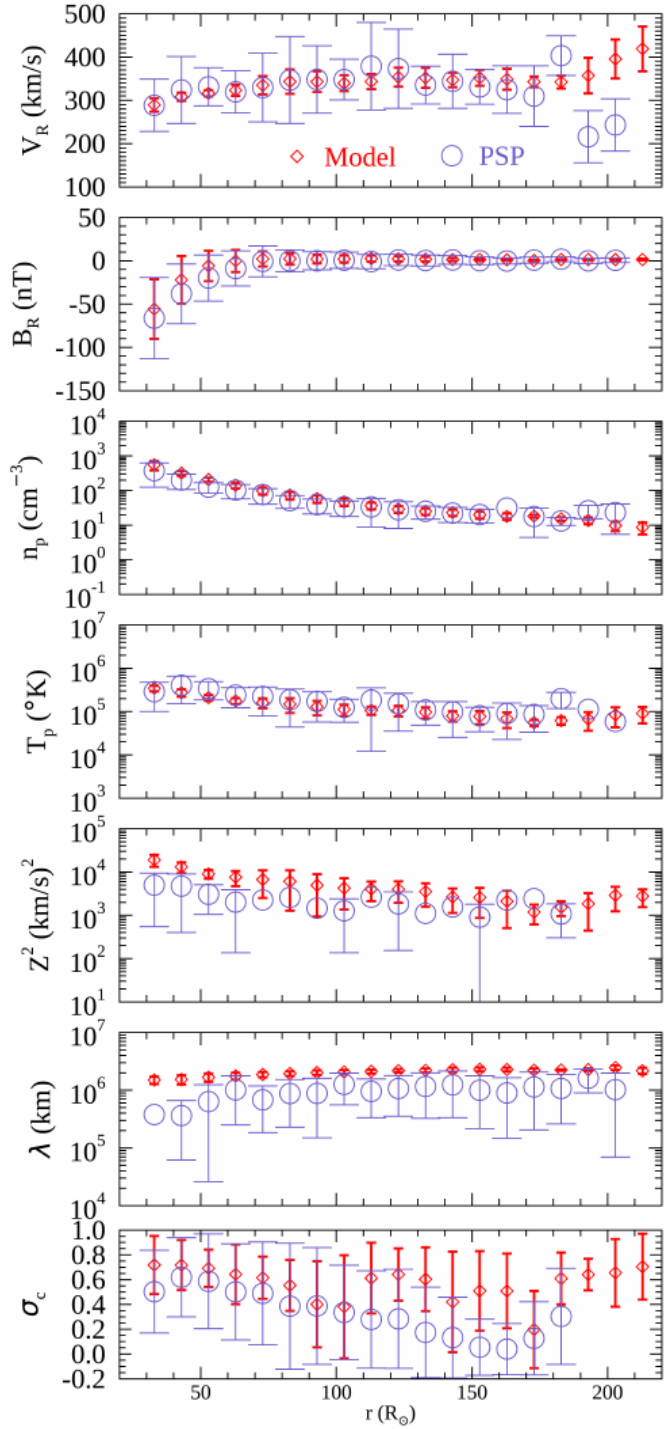


- For all orbits, general agreement is seen between model and observations
- Some transient high-speed streams seen in observations (especially in Encounter 1) are not captured in the model. This could be due to limited resolution of magnetograms used at inner boundary
- Modeled turbulence energy is often slightly larger (x1.5) than observations
- The observed correlation scale at PSP perihelia is several times smaller than model result. This could be an effect of dominant slab turbulence associated with radially aligned magnetic structures (Adhikari et al. 2020, DeForest et al. 2016)
- Some heliospheric current sheet crossings are captured (inferred from reversal of cross helicity)

Radial trends aggregrated from first five PSP orbits

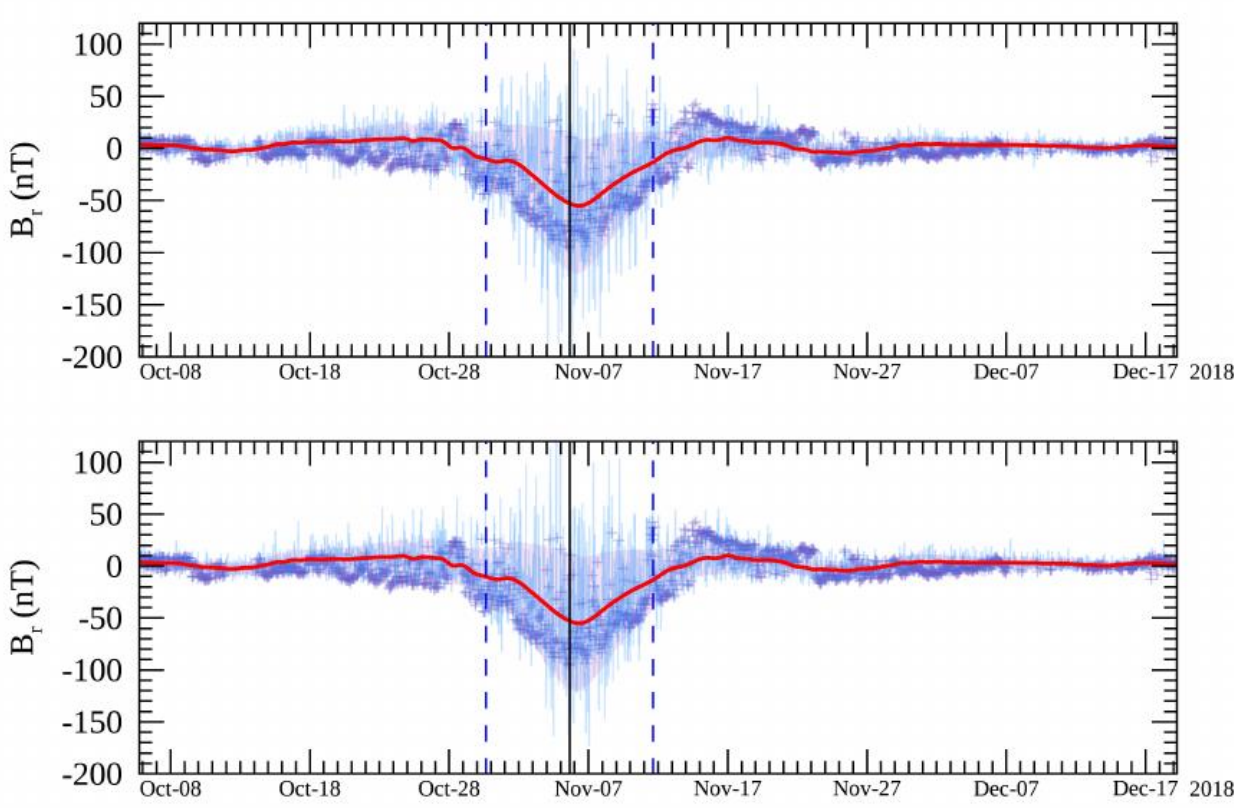
- Left: PSP data (symbols) aggregated from Orbits 1 to 5, plotted as a function of heliocentric distance. Red curves show results from the model, accumulated from five runs corresponding to the five respective orbits. The cross helicity has been sector rectified
- Right: Mean values within bins of 10 solar radii from PSP data (blue circles) and model (red diamonds). Bars above and below symbols represent the standard deviation.
- The averages reveal that radial trends in the mean flow are quite well captured by the model (regardless of transient features seen in time series plots). Broad trends in turbulence properties are also reproduced





Synthetic fluctuations constrained by global turbulence transport model (work in progress)

- Near-Earth magnetic-field fluctuations are observed to have near-Gaussian distributions (Padhye et al. 2001, Bandyopadhyay et al. 2020)
- We generate synthetic random magnetic fluctuations having a Gaussian distribution, along the PSP trajectory. The distributions are characterized by zero mean, and standard deviation is specified by the local turbulence amplitude from our model
- The Gaussian distributions generate radial fluctuations that are symmetric about the mean radial magnetic field (top panel in figure)
- However, PSP observations show that the fluctuations are skewed with non-zero skewness in their distributions. This is related to switchbacks
- We generate synthetic fluctuations with Gamma distributions (order 9), which better resemble the observed magnetic field. These synthetic fluctuations are shown in the bottom panel of the figure



Summary and References

- We use model based on Reynolds-averaging to obtain 3D solutions for both mean flow and statistical turbulence properties; results compared with data aggregated from the first five PSP orbits, which span heliocentric distances from 28 to 200 solar radii
- General agreement between model and data; radial trends (averaging out transient features over five orbits) are quite well captured by the model
- We generate synthetic fluctuations constrained by local turbulence amplitude from model – Gamma distribution resembles observations better than Gaussian distribution
- Planned improvements –
  - Higher-res B.C.s
  - Inclusion of transition region
- Future work can employ synthetic fluctuations in applications such as test particle tracing
- References -

  - Usmanov et al. 2018, ApJ. https://doi.org/10.3847/1538-4357/aad687
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  - Padhye et al. 2001, JGR. https://doi.org/10.1029/2000JA000293
  - Bandyopadhyay et al. 2020, ApJL. https://doi.org/10.3847/2041-8213/ab846e