Magnetohydrodynamic Simulation of the Inner Heliospheric Solar Wind within 7 AU: A Comparison with Ulysses Observations During 1990-2009

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Accurate The purpose of this work is to test the performance of the G3DMHD model [Wu et al., 2020, 2024]. G3DMHD is a data driven, time-dependent, global 3-D magnetohydrodynamic (MHD) model. The model has been proven to be effective in simulating the solar wind at and within 1 AU using the solar wind data from Wind and Parker Space Probe. In this work, we extend the G3DMHD model simulation domain out to 7 AU and perform three simulations. The simulated solar winds are compared with the Ulysses observations. Ulysses was the first (and still the only) spacecraft to orbit the Sun with a high inclination angle (~80°), monitoring the solar wind from pole to pole. Therefore, its data provide a stringent test of the G3DMHD model. Specifically, we use a sequence of source surface (2.5 $R_\odot$) maps, which are extrapolated from the (Mount Wilson Observatory) photospheric magnetic field maps using the potential field model, from 1990 to 2009 continuously covering two solar minima (1996 & 2008) and one solar maximum (2000), to drive G3DMHD. We consider the following three different inner boundary conditions: Case-A: Vr = 150 +500 fs km/s and γ = 1.67; Case-B: Vr = 150 +650 fs km/s and γ = 1.46; and Case-C: Vr = 150 +650 fs km/s and γ = 1.30, where Vr is the radial speed at 18 $R_\odot$, γ is the specific heat ratio, and fs is expansion factor. After comparing with the Ulysses observations (density, speed, temperature and magnetic intensity), the following results are found: (a) None of the three cases can lead to a satisfactory result for the four solar wind plasma and field parameters for all region/period being considered; (b) the solar wind speed is under-estimated in the pole region during solar minima for Case-A; (b) the solar wind temperature is under-estimated for Case-A for the entire time period and Case-B in solar minima; is over-estimated during 1997-2001 for Case-C; (c) the solar wind speed is over-estimated in solar maximum (2000) for both Case-B & Case-C; (d) the Case-C results in a better agreement for both solar wind density (Pearson correlation coefficient (cc) = 0.58; mean absolute squared error (MASE) = 0.64) and the solar wind velocity (cc = 0.56; MASE = 0.75) than for the solar wind magnetic intensity (cc = 0.40; MASE = 1.97) and temperature (cc = 0.38; MASE = 1.28). This simulation work suggests that the initial solar wind speed at the inner boundary, which is still difficult to measured, plays an important role. It is also suggested that a proper heating (controlled by γ) in the solar wind will need to be considered. * DISTRIBUTION A: Approved for public release: distribution unlimited.

MOTIVATION

- Reconstruction of solar wind plasma and field structures plays an important role in the infrastructure of space weather forecasting.
- The purpose of this study is to test the performance of G3DMHD at different radial distances from the Sun to 7 AU.
- G3DMHD is a data driven, time-dependent, three-dimensional (3-D) magnetohydrdynamic (MHD) model of the solar wind.
- We will perform global 3-D MHD simulation of the solar wind continuously from 1990 to 2009.
- Ulysses circled the Sun three times, with perihelion and aphelion altitude of 1.35 AU and 5.40 AU, respectively, and inclination of 79.11 deg.
- We will quantify the accuracy of G3DMHD using the Ulysses data.

METHODOLOGY

- A fully three-dimensional (3-D), time-dependent, magnetohydrodynamic (MHD) simulation code (Han 1977; Han, Wu, and Dryer, 1988) was used to propagate solar wind parameters at the inner boundary to 1 AU to compare with *in-situ* measurements. Realistic Global 3-D MHD was developed by Wu et al. [2020]
- The MHD model solves a set of ideal-MHD equations using an extension scheme of the two-step Lax–Wendroff finite-difference methods (Lax and Wendroff, 1960).
- An ideal MHD fluid is assumed in the Han model, which solves the basic conservation laws (mass, momentum, and energy) as shown with the induction equation to take into account the nonlinear interaction between plasma flow and magnetic field.

Simulation Domain and Setup

- The MHD equation set is solved in the Sun-center spherical coordinate system (r, θ, ϕ)
- The domain covers $-87.5° \le \theta \le 87.5°$; $0° \le \phi \le 360°$; $18\ R_\odot \le r \le 1518\ R_\odot$ (~0.08 – 7.06 AU; $R_\odot$: Solar radius)
- Open boundary conditions at θ = 87.5°, θ = -87.5°, and r = 1518 $R_\odot$ are used, so there are no reflective disturbances.
- A constant grid size of $\Delta r = 3\ R_\odot$, $\Delta\theta = 5°$, and $\Delta\phi = 5°$ are used, which results in 501 x 36 x72 grid sets.
- At the inner boundary r = 18 Rs, plasma and field parameters are taken from the modified WS model $V = V_1 + V_2 f_s^{-\alpha}$, where f_s is the magnetic expansion factor, V_1 = 150 km/s, V_2 = 500 km/s, and α = 0.4. [*Wu et al.*, 2020, *Solar Physics* 295: 25; JASTP,

- *Wu et al., 2020, Solar Physics* ***295:*** *25; doi: 10.1007/s11207-019-1576-6*
- *Wu et al., 2020, JASTP, https://doi.org/10.1016.j.jastp.2020.105211*

MHD Equations

$$\frac{D\rho}{Dt} + \rho \nabla \cdot V = 0 \tag{1}$$

$$\rho \frac{DV}{Dt} = -\nabla p + \frac{1}{\mu o}(\nabla \times B) \times B - \rho \frac{GM_s(r)}{r^2} r \tag{2}$$

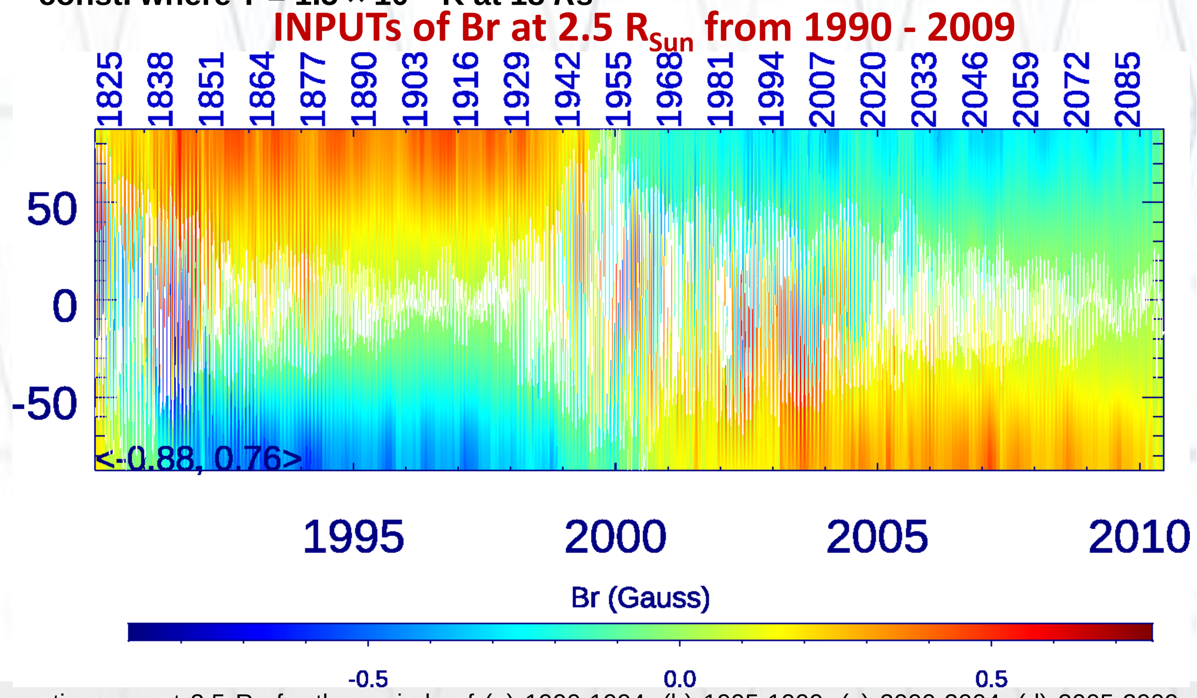
$$\frac{\partial}{\partial t}\left[\rho\rho + \frac{1}{2}\rho|V|^2 + \frac{|B|^2}{2\mu o}\right] + \nabla \cdot \left[V\left\{\rho e + \frac{1}{2}\rho|V|^2 + p\right\} + \frac{B \times (V \times B)}{\mu o}\right] = -v \cdot \rho \frac{GM_s(r)}{r^2} r \tag{3}$$

$$\frac{\partial B}{\partial t} = \nabla \times (V \times B) \tag{4}$$

Initial data set up at 18 Rs

- $r^2 Br$ = const; ; ρV = const. & $\rho = 2.35 \times 10^{-9}$ kg/km^3 and V is the average of Vr at 18 Rs; Proton temperature T at 18 Rs is calculated from $\rho(RT+V^2/2+gh)$ = const. where T = 1.5 × 10^6 °K at 18 Rs

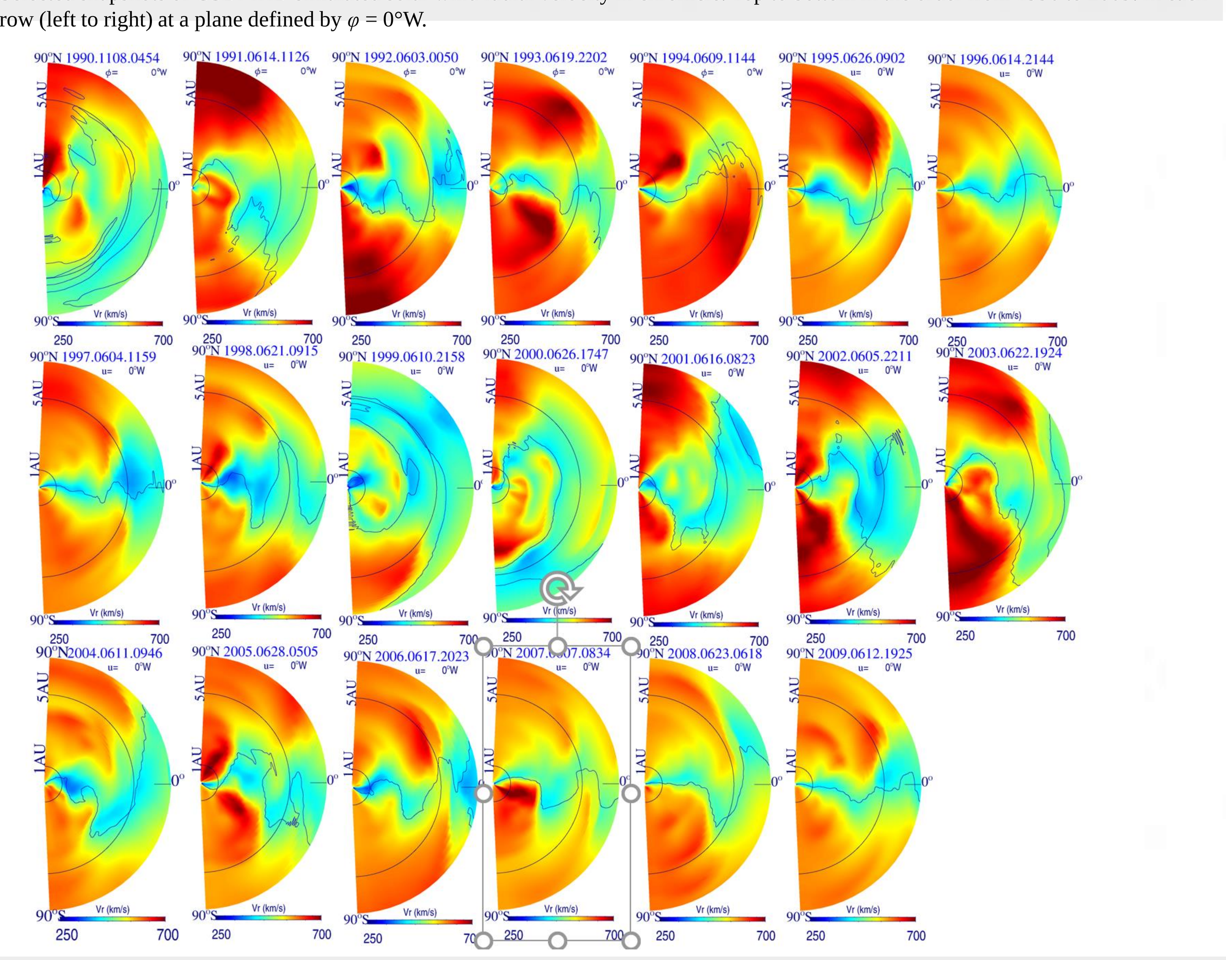
INPUTs of Br at 2.5 R_{Sun} from 1990 - 2009



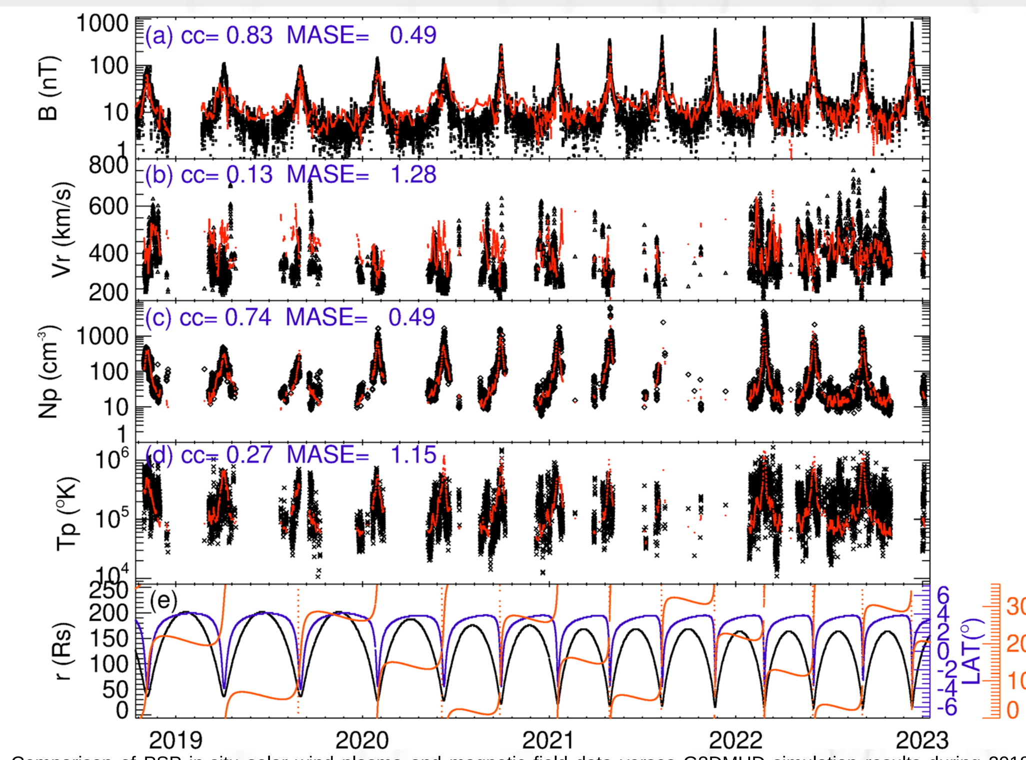
Synoptic maps at 2.5 $R_\odot$ for the periods of (a) 1990-1994, (b) 1995-1999, (c) 2000-2004, (d) 2005-2009, derived from Mountain Wilson Solar Observatory (MWO) photospheric measurements using the potential field source surface model. Magenta contours represent the location of heliospheric current sheet (HCS), i.e., Br = 0. Carrington rotation numbers are marked on the top of each figure. Y-axis represents the latitude of maps. X-axis represents the time sequence Year (units is in year). Values of minimum & maximum of Br are marked on the left-bottom corners.

G3DMHD Simulation Results during 1990-2009

Selected snapshots of G3DMHD simulated solar wind radial velocity in chronicle. Top to bottom in the order from 1990 to 2009. In each row (left to right) at a plane defined by φ = 0°W.



Solar Wind evolution during 2018-2022 (Wu et al., 2024)



Comparison of PSP in-situ solar wind plasma and magnetic field data verses G3DMHD simulation results during 2018-2022. Panels from top to bottom panels are temperature (units in degrees Kelvin, °K), magnetic field (B in nT), velocity in the radial (r) direction (V_r in km/s), number density (N_p in #/cc), and the location of the Parker Solar Probe (PSP) spacecraft (black-, blue-, and orange-lines are the distance from the center of the Sun to the PSP, latitude, and longitude location of the PSP, respectively. The Pearson correlation coefficient (cc) and MASE for the modeled solar wind are marked on the top of each panel.

Wu, Liou, Wood, Wang, APJ, 977:150, 2024. DOI 10.3847/1538-4357/ad8d54

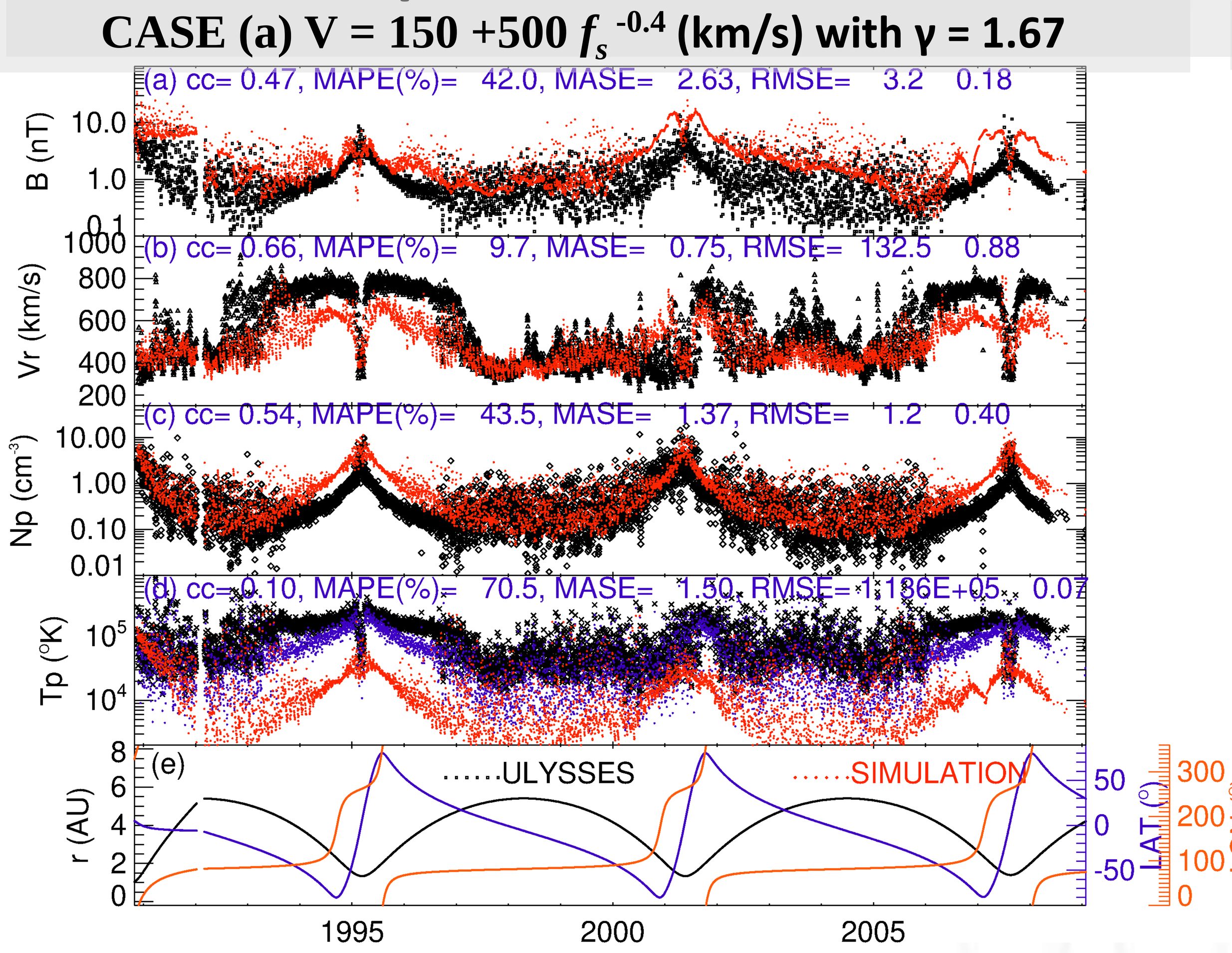
CASE	cc	MASE
	B, Vr, Np, Tp	B, Vr, Np, Tp
(a)	0.47, **0.66**, 0.54, 0.10	2.63, 0.75, 1.37, 1.50
(b)	0.48, 0.56, 0.56, 0.28	1.24, 0.74, 0.65, 1.07
(c)	0.40, 0.56, **0.58**, 0.38	0.97, 0.75, **0.64**, **1.28**

Table 3.2 Model validation metrics for the CaseC.

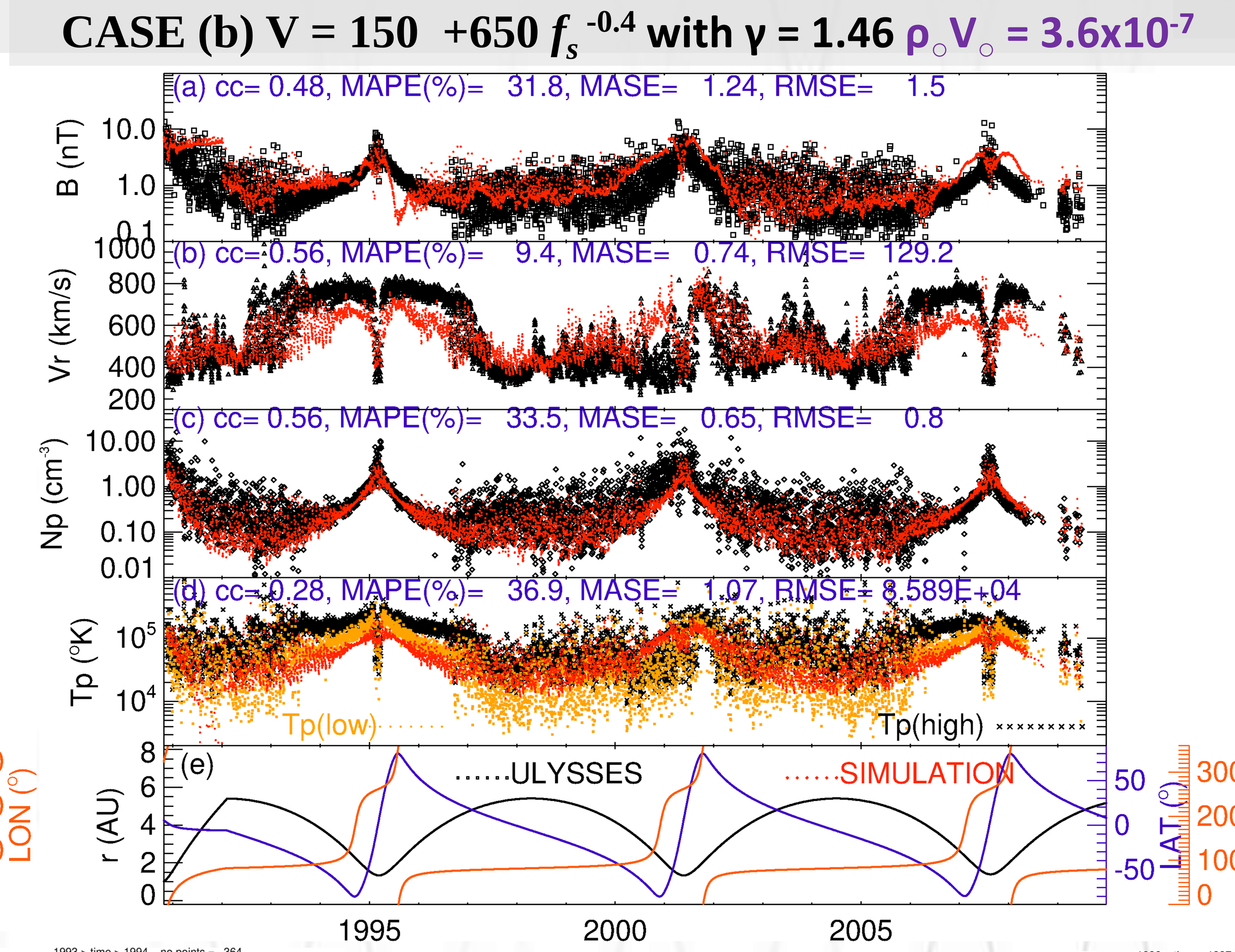
Year	B		Np		Vr		Tp	
Parameter	cc	MASE	cc	MASE	cc	MASE	cc	MASE
1990	0.10	1.65	0.22	1.26	0.19	2.61	0.46	3.80
1991	-0.33	2.39	0.45	0.81	0.11	1.56	0.06	1.76
1992	0.23	1.73	0.04	1.20	0.04	1.20	-0.01	1.37
1993	0.13	1.27	0.21	1.07	0.59	1.17	0.32	1.06
1994	0.85	0.52	0.92	0.44	0.17	4.06	0.58	1.58
1995	0.63	0.72	0.61	0.52	0.74	1.01	0.39	1.44
1996	-0.07	1.88	-0.07	1.16	0.08	2.46	0.17	1.29
1997	0.08	1.27	0.11	1.07	0.56	1.41	0.25	2.91
1998	0.04	1.15	0.07	1.09	0.02	1.84	0.01	2.04
1999	-0.06	1.21	-0.03	1.03	-0.09	2.41	-0.03	2.56
2000	0.27	1.29	0.14	0.98	-0.11	3.48	0.01	5.14
2001	0.10	1.05	0.34	0.90	0.55	0.99	0.23	2.81
2002	0.04	1.05	0.01	0.97	0.24	1.26	0.16	2.14
2003	0.05	1.09	0.02	1.00	0.15	1.06	0.08	1.30
2004	-0.15	1.21	-0.07	1.01	-0.05	1.43	-0.12	1.60
2005	0.06	0.98	0.00	0.96	0.20	1.34	0.03	1.61
2006	0.12	1.61	0.32	0.99	0.31	3.08	0.30	1.54
2007	0.24	0.98	0.58	0.65	0.58	1.02	0.11	2.34
2008	0.78	1.58	0.74	1.26	0.29	4.51	0.60	2.99
2009	0.03	1.32	-0.32	1.35	-0.05	1.61	-0.26	3.17
1990-2009	0.40	0.97	0.58	0.64	0.56	0.75	0.38	1.28
1994.7-1995.7	0.46	0.91	0.56	0.60	0.73	1.02	0.29	1.61
2007.1-2008.1	0.18	1.05	0.57	0.66	0.58	1.01	0.14	2.40

Comparison of G3DMHD Simulation Results (in Red dots) verses Ulysses observation for the period of 1990-2009

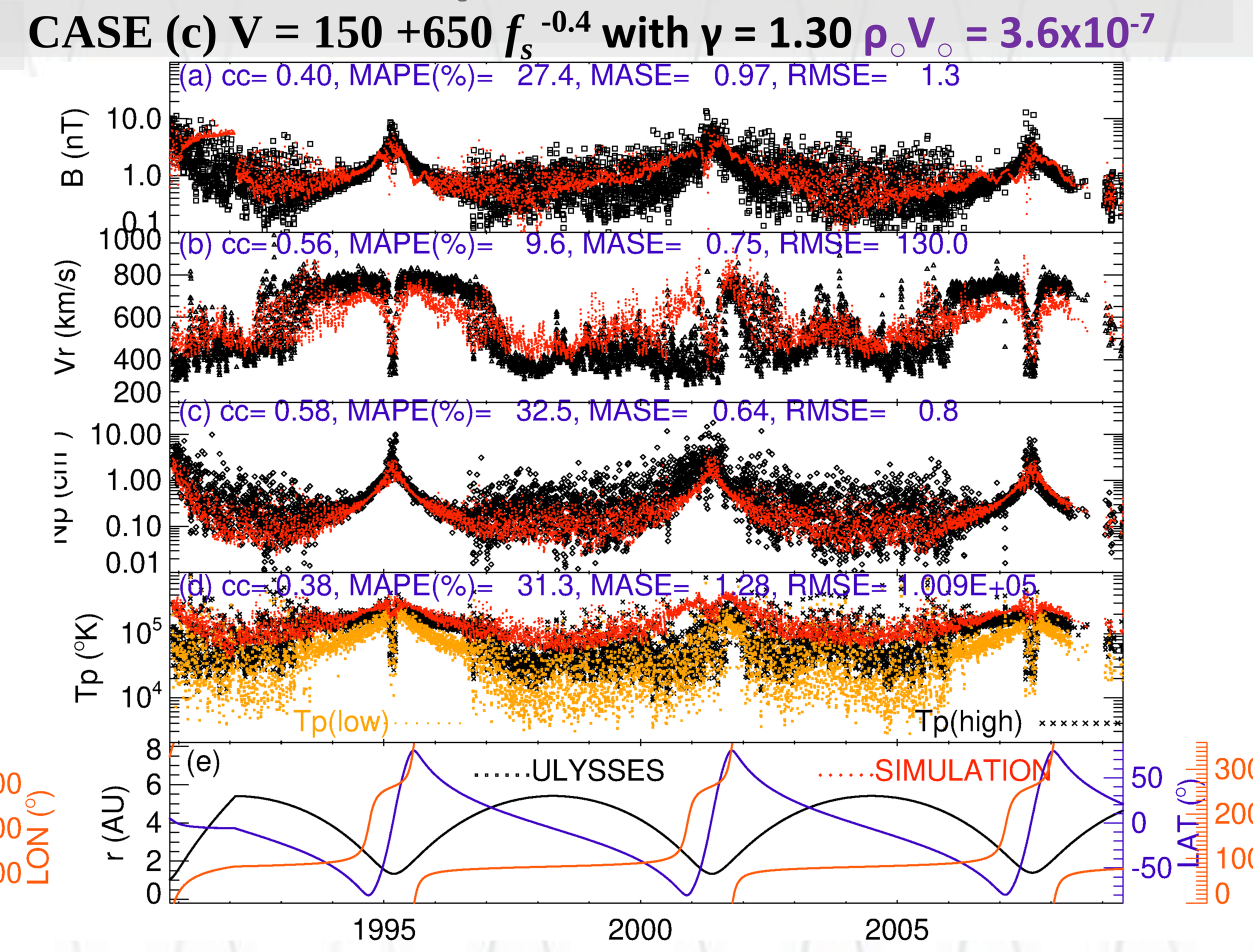
CASE (a) V = 150 +500 $f_s^{-0.4}$ (km/s) with γ = 1.67

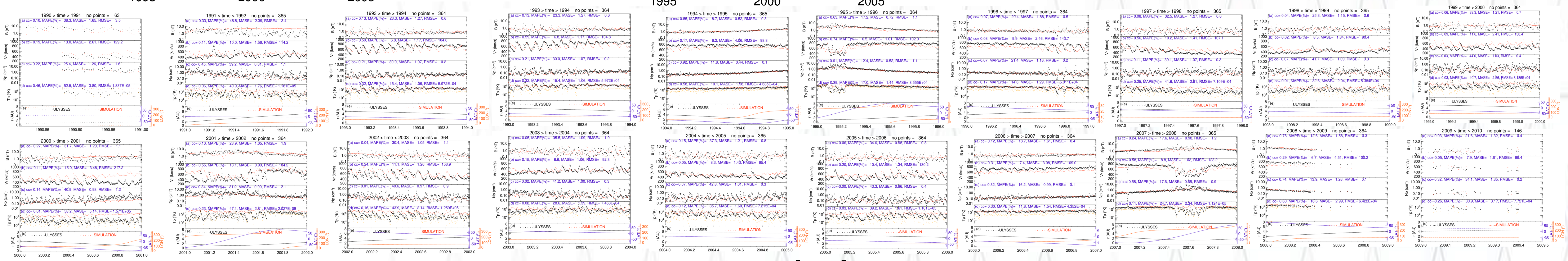


CASE (b) V = 150 +650 $f_s^{-0.4}$ with γ = 1.46 $\rho_\circ V_\circ = 3.6 \times 10^{-7}$



CASE (c) V = 150 +650 $f_s^{-0.4}$ with γ = 1.30 $\rho_\circ V_\circ = 3.6 \times 10^{-7}$





Conclusion

- None of the three cases can lead to a satisfactory result for the four solar wind plasma and field parameters for all region/period being considered;
- The solar wind speed is under-estimated in the pole region during solar minima for Case-A;
- the solar wind temperature is under-estimated for Case-A for the entire time period and Case-B in solar minima; is over-estimated during 1997-2001 for Case-C;
- The solar wind speed is over-estimated in solar maximum (2000) for both Case-B & Case-C;
- The Case-C results in a better agreement for both solar wind density (Pearson correlation coefficient (cc) = 0.58; mean absolute squared error (MASE) = 0.64) and the solar wind velocity (cc = 0.56; MASE = 0.75) than for the solar wind magnetic intensity (cc = 0.40; MASE = 1.97) and temperature (cc = 0.38; MASE = 1.28).
- This simulation work suggests that the initial solar wind speed at the inner boundary, which is still difficult to measured, plays an important role. It is also suggested that a proper heating (controlled by γ) in the solar wind will need to be considered.

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