Validation for Solar Wind and CME Prediction

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I. Validation for Solar Wind Prediction

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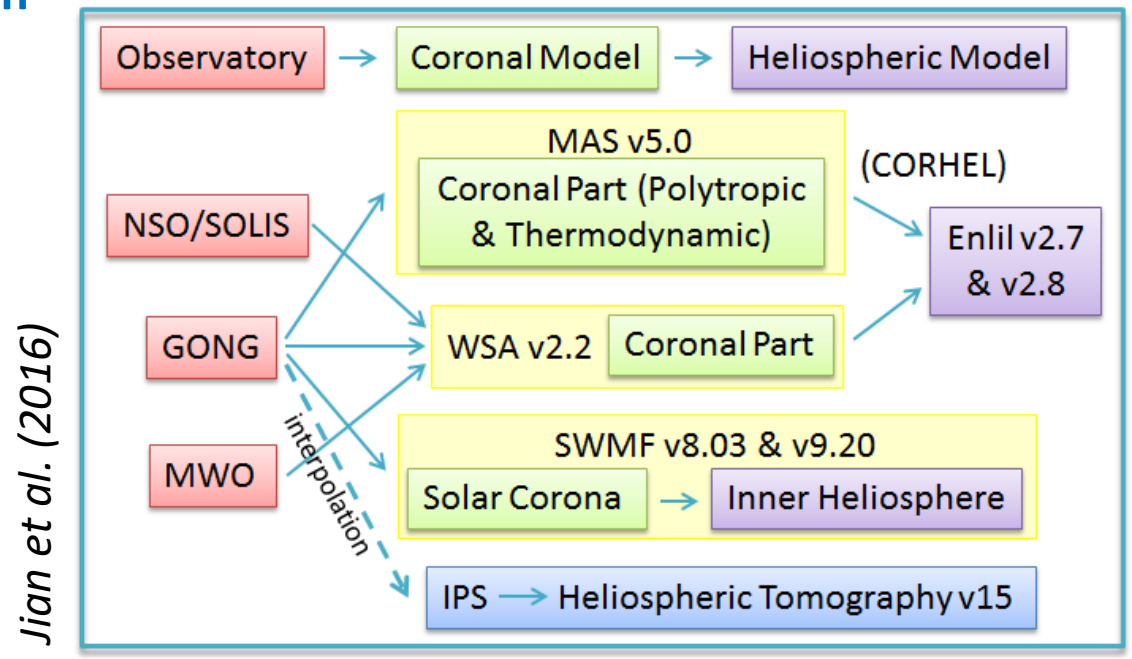
Widely-Used Coronal and Heliospheirc Models Installed at the CCMC

GONG: Global Oscillation Network Group
NSO/SOLIS: National Solar Observatory at Kitt Peak,
Synoptic Optical Long-term Investigations of the Sun
MWO: Mount Wilson Observatory

MAS: MHD-Around-a-Sphere model
WSA: Wang-Sheeley-Arge model
SWMF: Space Weather Modeling Framework
IPS: Interplanetary Scintillation



Introduction of the Model Description, Resolution, and Inner Boundary Condition

Model	Description			Resolution		Inner Boundary Condition
WSA v2.2 coronal part, up to 21.5 *Rs*	PFSS+Schattern current sheet model, semiempirical			Magnetogram with a smoothed resolution of 2.5° in latitude and longitude	101×92×182 (radial × latitude × longitude) → (0.20 *Rs*, 2.0°, 2.0°)	Radial surface field, magnitude is set so that its line of sight component matches magnetogram
MAS v5.0 coronal part, up to 30 *Rs*	3-D MHD model	Polytropic	Zero beta approximation	Magnetogram with a resolution of 1° in latitude and longitude	101×101×128 → (0.29 *Rs*, 1.8°, 2.8°)	Base of corona: T = 1.8 MK and N = 2×10^8 cm^{-3}
		Thermo-dynamic	Full thermodynamic energy equation		151×101×182 → (0.19 *Rs*, 1.8°, 2.0°)	Chromosphere: T = 0.02 MK and N = 2×10^{12} cm^{-3}
Enlil heliospheric model, up to 430 *Rs*	3-D MHD model for super-Alfvenic solar wind, driven by WSA, MAS, and possible by other models too, only one temperature			v2.8, coupling with WSA	1024×120×360 → (0.40 *Rs*, 1.0°, 1.0°)	21.5 *Rs*: V_{slow} = 200 km/s, V_{fast} = 700 km/s, T = 2 MK, and N = 200 cm^{-3}
				v2.7, coupling with MAS	320×60×180 → (1.25 *Rs*, 2.0°, 2.0°)	30 *Rs*: V_{slow} = 250 km/s, V_{fast} = 650 km/s, T = 0.6 MK, and N = 150 cm^{-3}
SWMF, 3-D MHD model, up to 500 *Rs*, separate ion and electron temperatures	v8.03	Starting from corona, semiempirical solar wind heating		Nonuniform grid. Within 24 *Rs*: cell size ranging 0.025-0.75 *Rs*. Heliospheric part (starting at 20 *Rs*): a minimum cell size of 1 *Rs*		Top of chromosphere: T = 0.02 MK and N = 2×10^{10} cm^{-3}
	v9.20	Starting from the upper chromosphere, adding physics-based turbulent Alfven wave dissipation for coronal heating and solar wind acceleration		Non-uniform grid. Inside 1.7 *Rs*: the angular resolution of 1.4°. Coronal part (chromosphere to 24 *Rs*): cell size ranging 0.001-0.8 *Rs*. Heliospheric part: 2 *Rs* within the current sheet and 8 *Rs* elsewhere (higher resolution of 1 *Rs* within the current sheet in a new refinement which is in progress)		Top of chromosphere: T = 0.05 MK and N = 2×10^{11} cm^{-3}
IPS tomography v15	3-D reconstruction using a kinematic solar wind model and tomographically fitting it to IPS observation			Time cadence of 6 h (can be increased to 3 h after using more worldwide IPS data)		N/A

Jian et al. (2016)

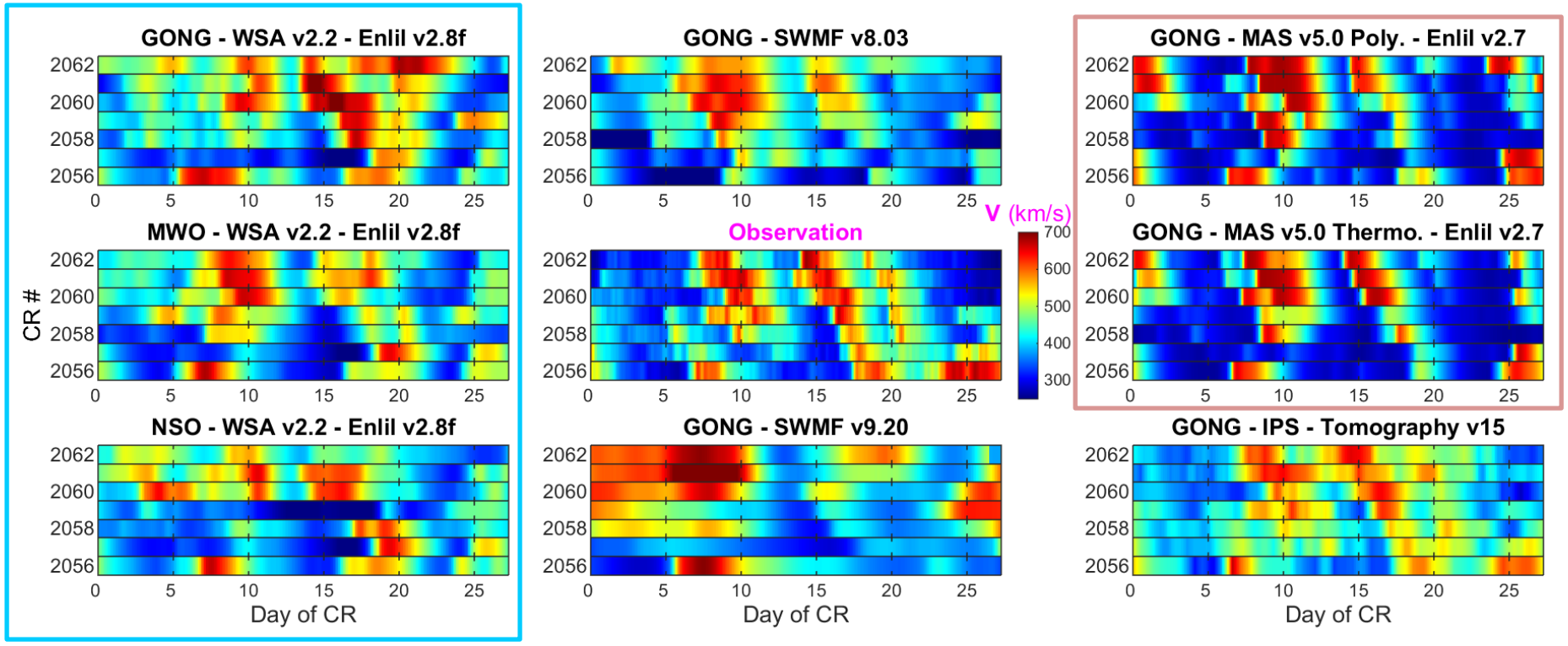
Performance Metrics for Solar Wind Simulation

Jian et al. (Space Weather, 2015, 2016) provided sample performance metrics using four parameters (V, B, N, T)

1. Visual comparison
2. Mean square error for time series of solar wind parameters (without & with normalization)
3. Model/observation ratio
4. Correlation between model and observation
5. Capturing IMF sectors (automatic identification of sectors)
6. Capturing slow-to-fast stream interaction regions (SIRs) (automatic identification of SIRs)
7. Capturing the latitudinal variations of solar wind
8. Statistics of solar wind at low latitudes and mid-to-high latitudes

Ulysses

Comparison of Solar Wind Speed at Earth Orbit in 2007

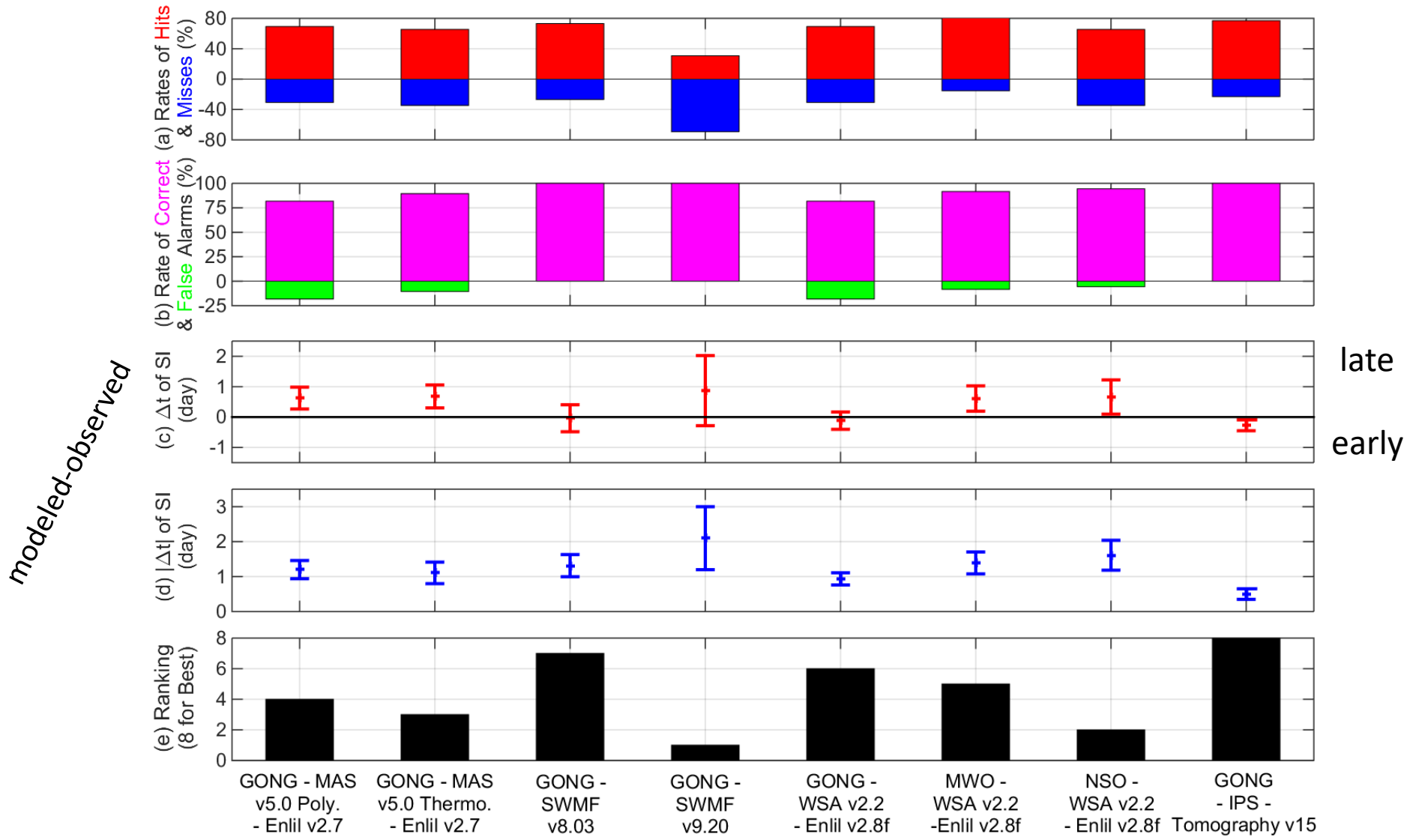


After Jian et al. (2015)

Large variability from the simulation results

- WSA v2.2 – Enlil v2.8 model using magnetograms from different sources
- Multiple models using the same GONG magnetogram
- Different versions of SWMF perform very differently

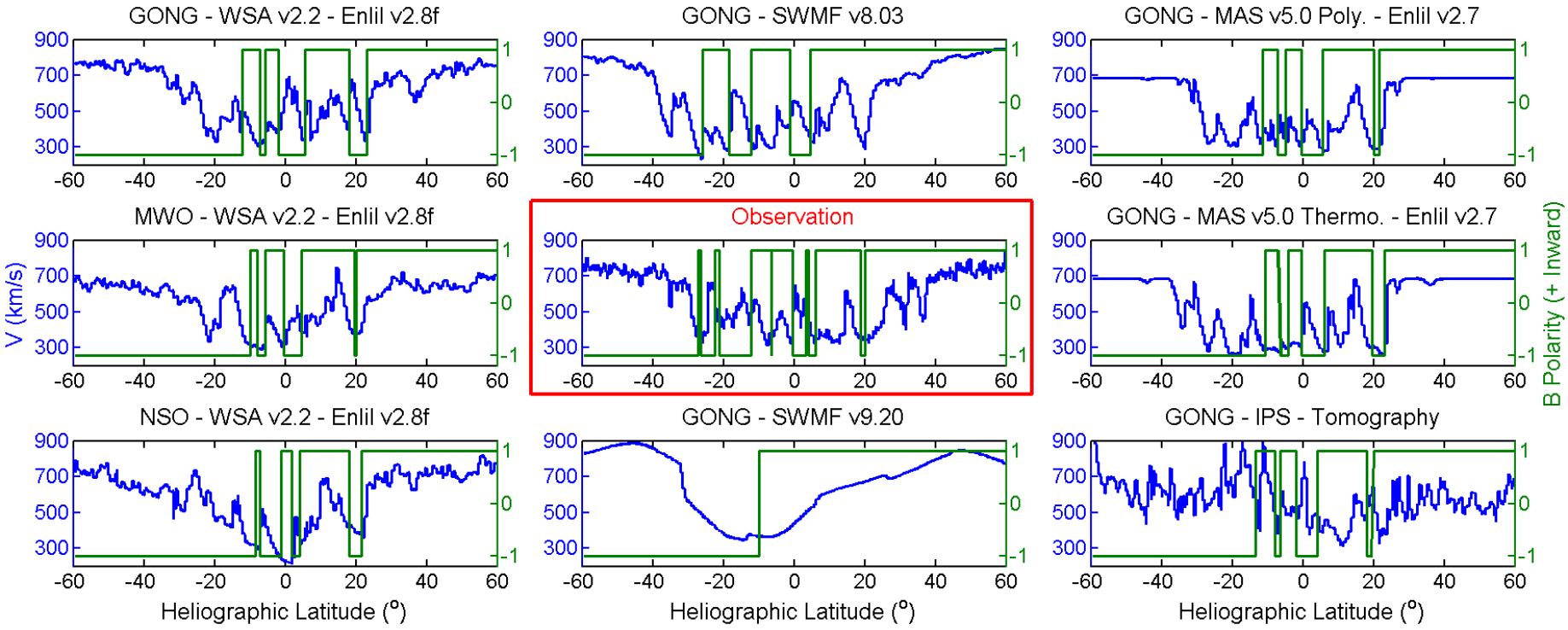
Capabilities of Capturing SIRs



After Jian et al. (2015)

Capabilities of Capturing Latitudinal Variations of Solar Wind

Solar Wind Speed & IMF Polarity



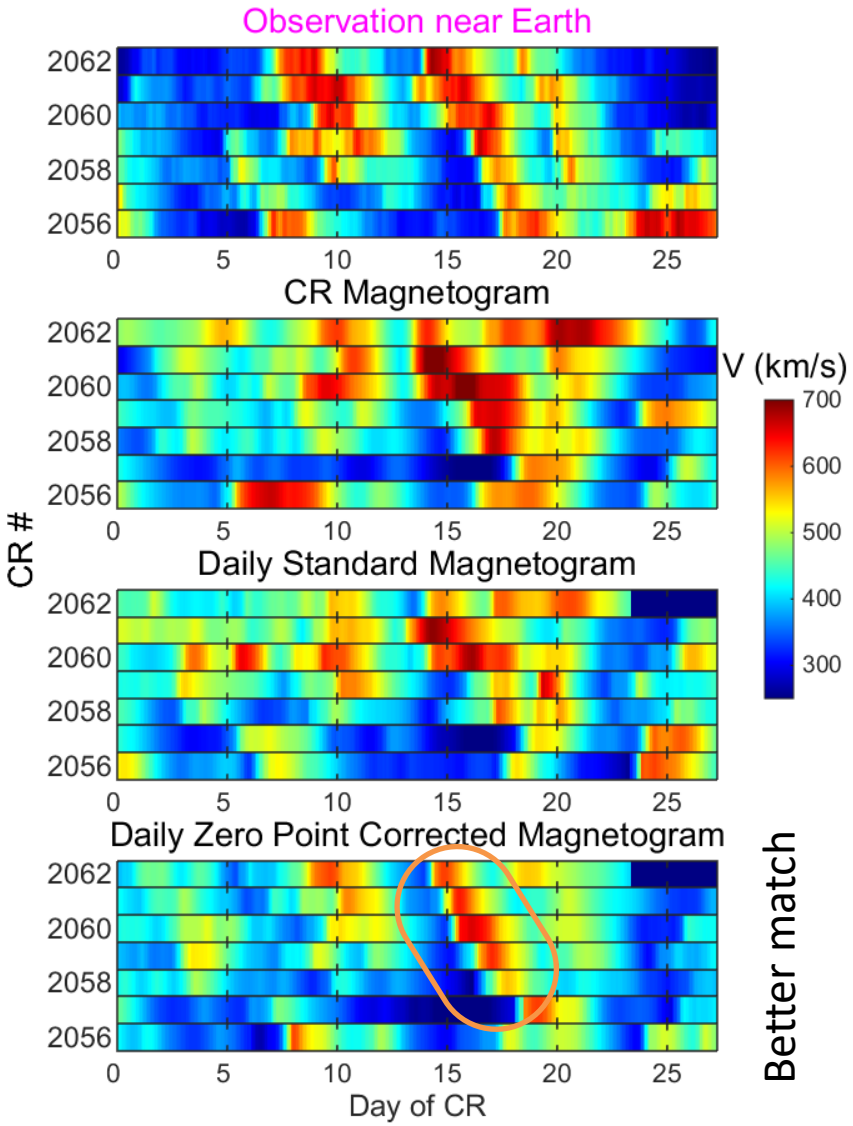
Jian et al. (2016)

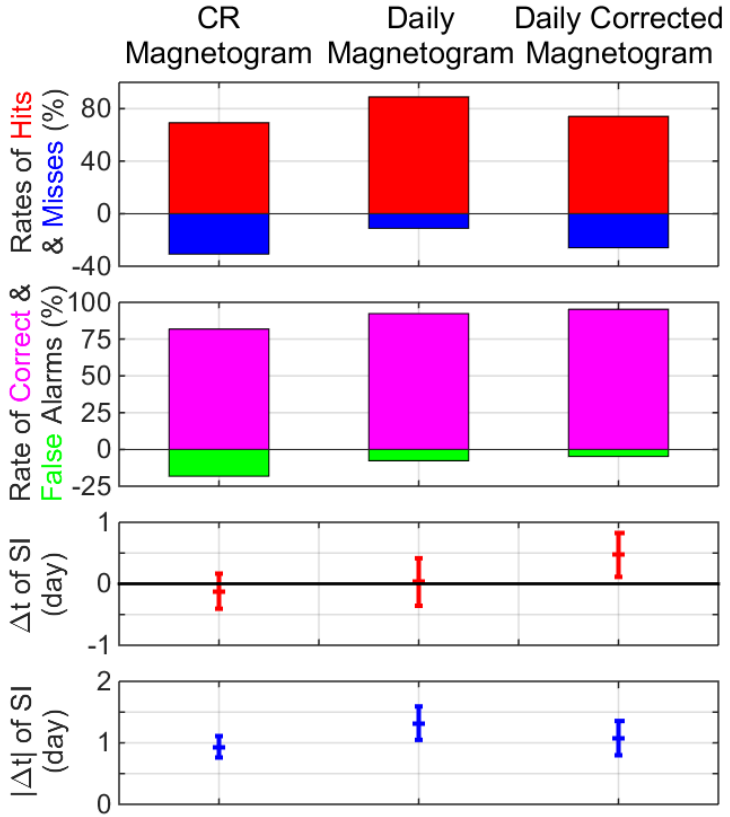
Summary of the Model Evaluation for 2007

Synoptic Map	Model		Strength			Weakness		
	Solar Corona Part	Inner Heliospheric Part						
MWO	WSA v2.2	Enlil v2.8	lowest RMSE for N_p and B	match well with median B at all latitudes	match well with median N_p at all latitudes	underestimate the fast wind V at middle to high latitudes		
NSO/ SOLIS			best match for low-latitude median B and T_p and high-latitude median V			largest RMSE for normalized V, second least correlation with V		
GONG			second highest correlation for V			N/A		underestimate B at all latitudes
	MAS v5.0 Polytropic	Enlil v2.7	lowest RMSE for V, normalized V, N_p, and T_p; highest correlation for N_p, B, and T_p		highest correlation for V	N/A	underestimate the fast wind V at middle to high latitudes; overestimate low-latitude median N_p	
	MAS v5.0 Thermodynamic		second lowest RMSE for normalized V; second highest correlation for N_p, B, and T_p			overestimate low-latitude median N_p most, underestimate low-latitude median B and T_p most		
	SWMF v8.03		match low-latitude median V best			largest RMSE for N_p, normalized N_p, B, and T_p; lowest correlation for B and T_p		
	SWMF v9.20		capture the high-latitude hot solar wind well; lowest RMSE for T_p and normalized B			latitudinal variations are much smoothed; produce north-south asymmetry not observed by Ulysses; largest RMSE for V		
IPS Tomography v15			N/A			produce transient structures not observed by Ulysses at middle to high latitudes; could not capture the latitudinal variation of N_p; lowest correlation for V and N_p; mismatch high-latitude median V and N_p most		

Jian et al. (2016)

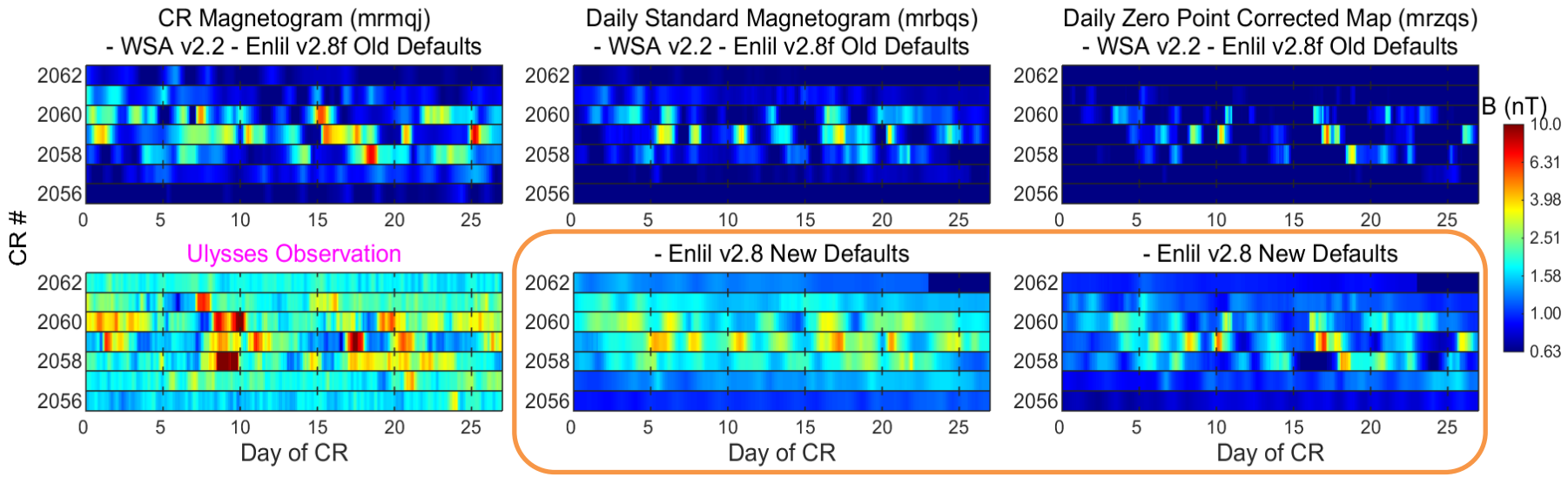
WSA v2.2 – Enlil v2.8 Using Different Magnetogram Synoptic Maps from GONG





Riley et al. (2014) showed the conversion factor between different observatories can be > 10, and it varies with latitude

WSA v2.2 – Enlil v2.8 Using Different GONG Magnetograms and Different Parameter Settings



Jian et al. (2016)

- **More than 10 parameters** are used in setting the ambient wind conditions at ENLIL's inner boundary
- They have been recently added in the WSA-Enlil result page as the **control file**
- The new setting has recently been implemented at CCMC

II. Validation of CME Prediction Using WSA-Enlil+Cone Model

Collaborators: D. Odstrcil, M. L. Mays

Thanks to NSF Award AGS-1321493

Introduction of the Modeling System

- The WSA-Enlil model uses kinematic properties of CMEs inferred from coronal and/or heliospheric observations to launch a CME-like **hydrodynamic** structure at **21.5 Rs** (Arge and Pizzo, 2000; Arge et al., 2004; Odstrcil et al., 2005)
- The Enlil model at CCMC has been gradually evolving for run-on-request, but it has been kept as **v2.7** for the predictions at NOAA/SWPC
- Main new features used in the present **v2.9** of Enlil model
  - Using a sequence of the WSA maps computed from the closest GONG daily synoptic magnetogram
  - Self-correcting model free parameters based on monthly-averaged in situ measurements at 1 AU
  - More reliable identification of disturbances by multi-grid computations
  - Revised the volumetric heating that is independent on the numerical time step variations
  - Enhanced visualization, synthetic white-light images, and input for SEP model and IPS tomography

CME Parameters Used as Model Input

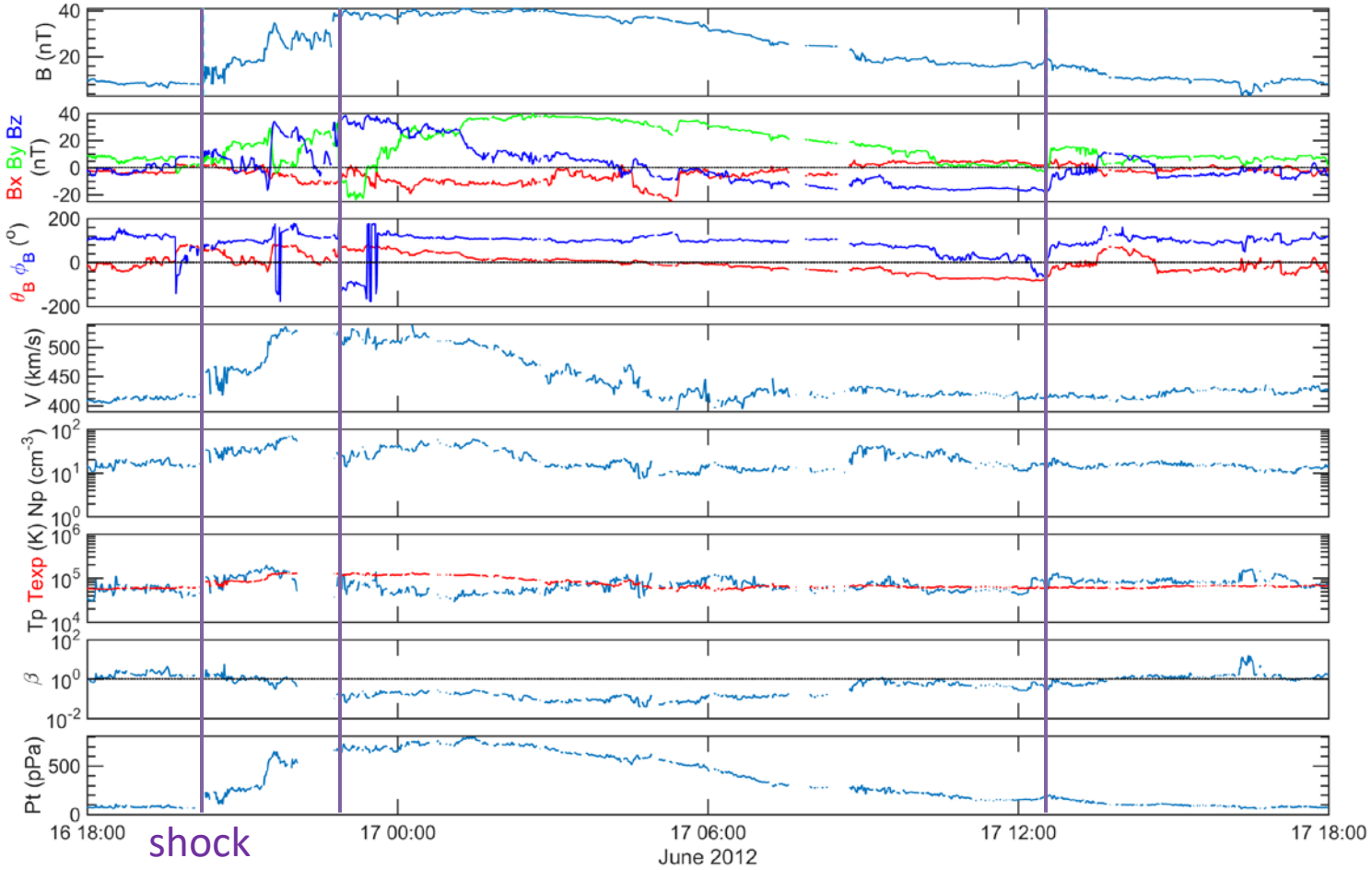
Cone	date	Leading edge at 21.5 Rs at this time (yyyy-mm-ddThh:mm)
	lat	Heliographic latitude of the cone axis (deg)
	lon	Heliographic longitude of the cone axis (deg)
	radcld	Half-width of the cone (deg)
	vcld	Velocity of the cone (km/s)
	dcld	Density of the cone as factor of mean stream value
	tcld	Temperature of the cone as factor mean stream value
Cavity if radcav > 0	radcav	Radius of the cavity as factor of radcld
	dcav	Density of the cavity as factor of mean stream value
	tcav	Temperature of the cavity as factor of mean stream value

- The geometrical CME properties are approximated by the Cone model
- At CCMC, CME parameters are determined using
  - Stereoscopic CME Analysis Tool (StereoCAT) based on tracking specific CME features (Pulkkinen et al., 2010)
  - **Since about 2014**, CME Analysis Tool (CAT) to capture the volumetric structure of CMEs (Pizzo and Biesecker, 2004; Millward et al., 2013)
- The CME parameters and simulation graphic outputs since 2010 → CCMC/DONKI
- The Enlil simulation results including graphic outputs in 2007-2016 at **Helioweather**
- The simulations use a **medium** spherical grid size of 512×60×180 (r, θ, ϕ) to cover 0.1-2.1 AU in radius, ±60^o in latitude, and 360^o in longitude
- Output is of ~4-min cadence at Earth

Recent History of Our Validation Effort

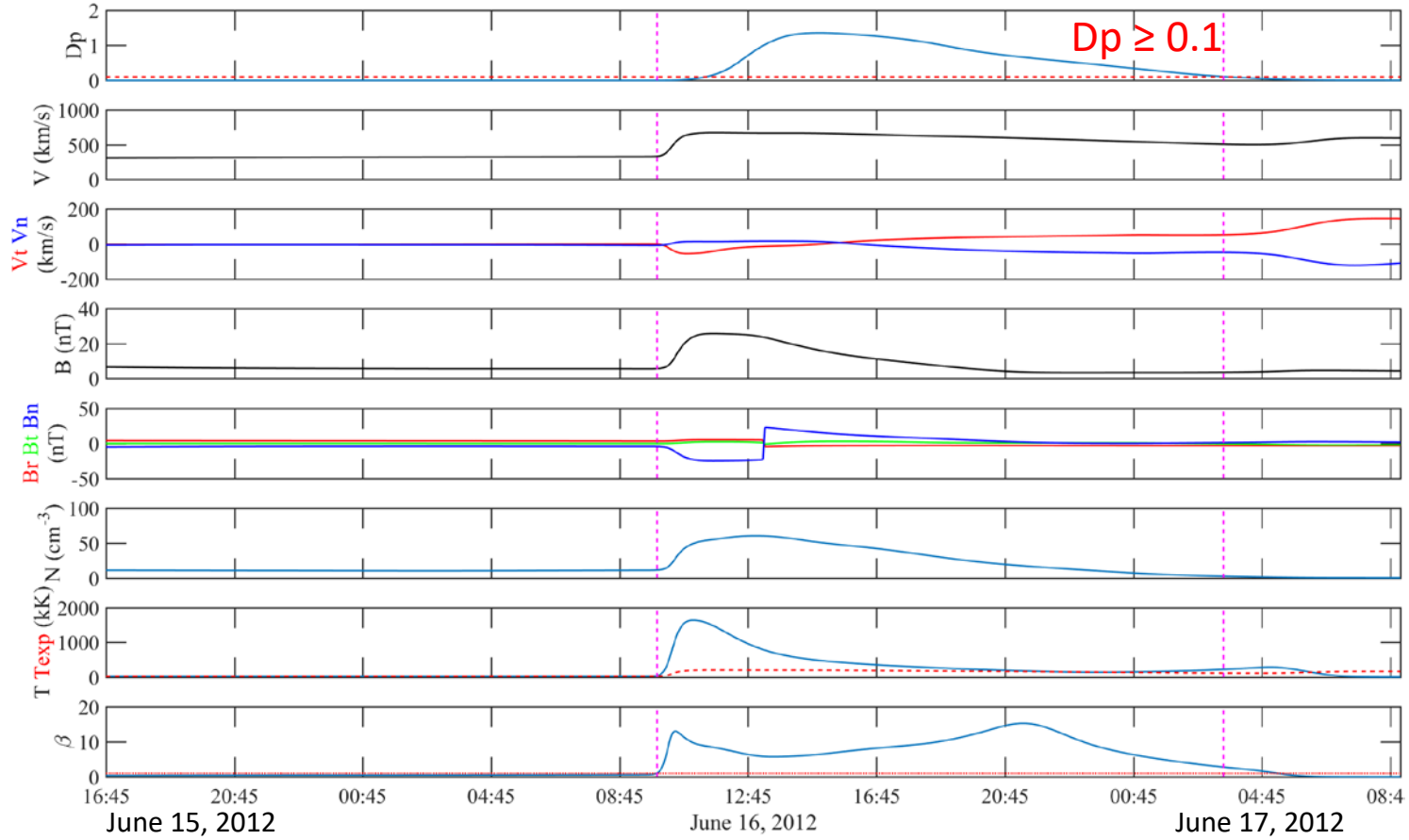
- 2016
  - CMEs in 2012-2015
  - CME input from CCMC/SWRC
- 2017
  - CMEs with an initial speed > 400 km/s in 2007-2016
  - CME input from the **fixed-phi** fitting (angular width = 60^{o}) from the joint Heliospheric Cataloguing, Analysis and Techniques Service (HELICATS) project
- 2018
  - CMEs in 2010-2016
  - CME input from CCMC/SWRC (most are from real-time prediction)
  - Use GONG daily zero point corrected synoptic magnetograms
  - Self-correcting model free parameters based on monthly-averaged in situ measurements at 1 AU

A Survey of Interplanetary CMEs (ICMEs)



- **ICMEs = Magnetic Clouds (MCs) + ICMEs without well-defined flux ropes**
- Multiple (not all) criteria are used: increased magnetic field, field rotations over a large scale, lower than expected proton temperature, low β, bidirectional suprathermal electron strahls, speed decrease, increase of total pressure (Pt), etc.
- ICMEs at L1 are surveyed using 1-min OMNI data for 2010-2016. The ICME/MC catalogs from Richardson and Cane, Nieves-Chinchil, Wu and Lepping are used as references

Identification of Simulated ICMEs



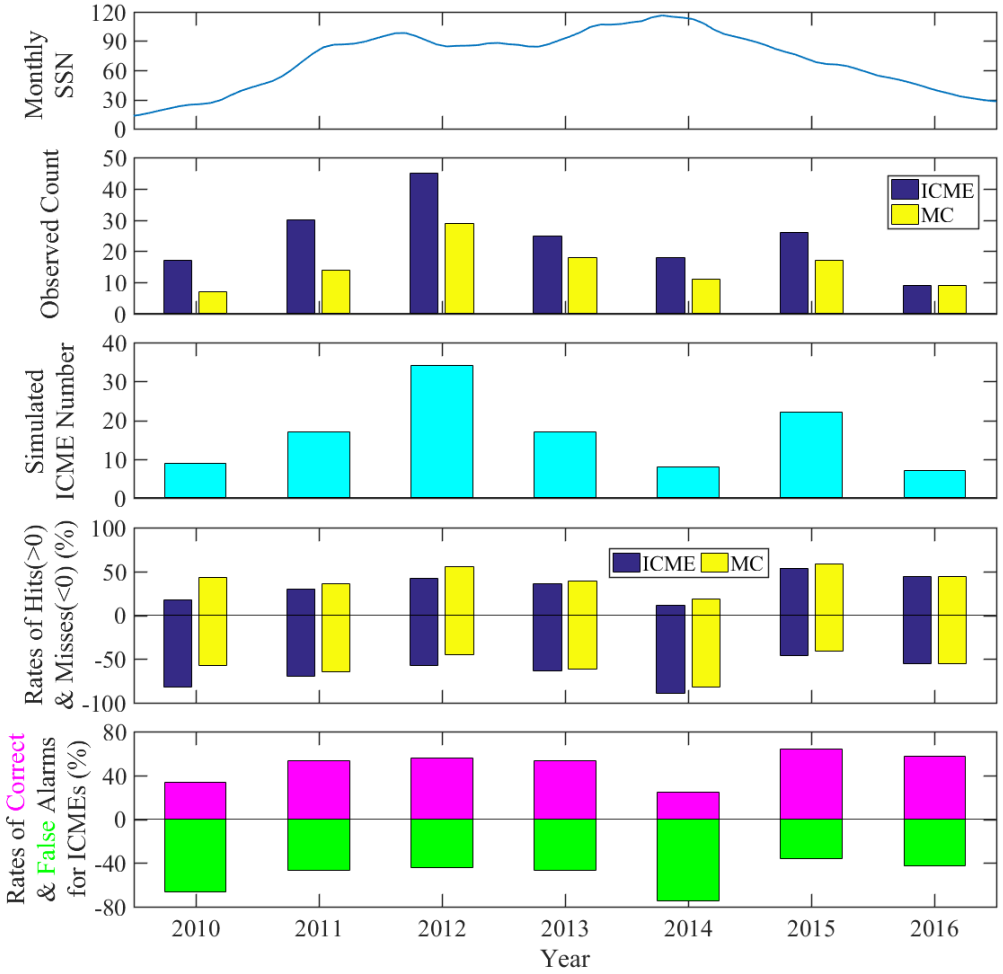
- ICMEs in simulations are identified by requiring Dp ≥ 0.1
- ICME start time
  - The closest time when V and/or B increases sharply, earlier than Dp ≥ 0.1
  - If there is no sharp increase of V or B, choose the time when V and/or B starts to increase
- ICME end time: at the end time of Dp ≥ 0.1 or when solar wind parameters return to ambient, whichever comes last

Statistics of ICME Prediction in 2010-2016

	Observed	Captured	Rate of Hits (%)	Rate of Misses (%)	Simulated	Rate of Correct Alarms (%)	Rate of False Alarms (%)	Absoulte Offset of Arrival Time (hr)
ICMEs	170	60	35.3	64.7	114	52.6	47.4	11.5±1.4
MCs	105	47	44.8	55.2	N/A	N/A	N/A	13.4±1.8
ICMEs with shock	99	46	46.5	53.5	N/A	N/A	N/A	9.2±1.2

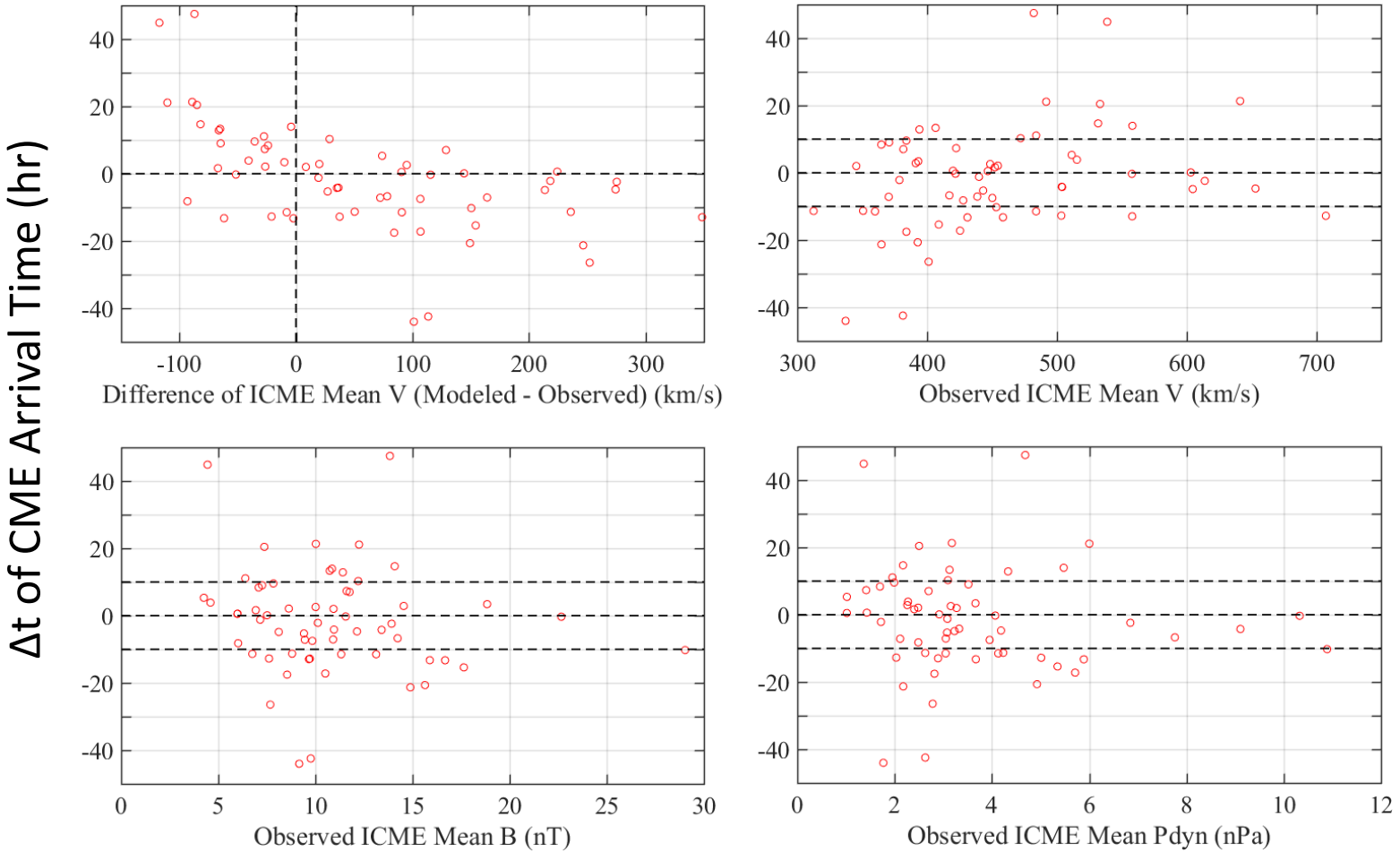
- At Earth, 114 ICMEs are identified in the simulation data
- If there are shocks, shock time is used as the ICME start time
- A slight preference (55%) of early arrival
- For the same CME, the arrival time from the Enlil simulation with different settings can readily differ by 6 hours or more

Annual Variations of ICME Prediction



- The performance of CME prediction varies much from year to year
- The rates of hits and correct alarms drop in 2014, possibly related to the change of the CME fitting methods at CCMC and the less help from STEREO remote observations

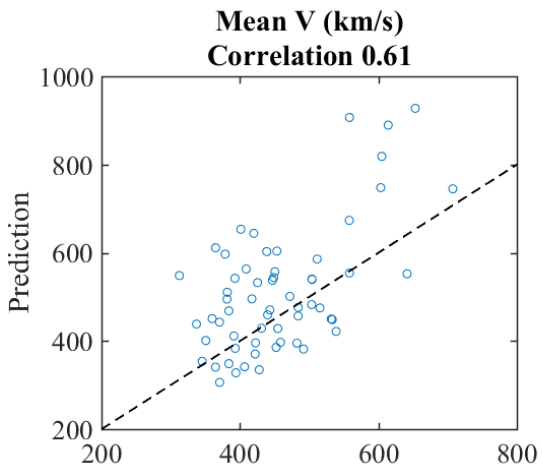
Factors Affecting the ICME Arrival Time



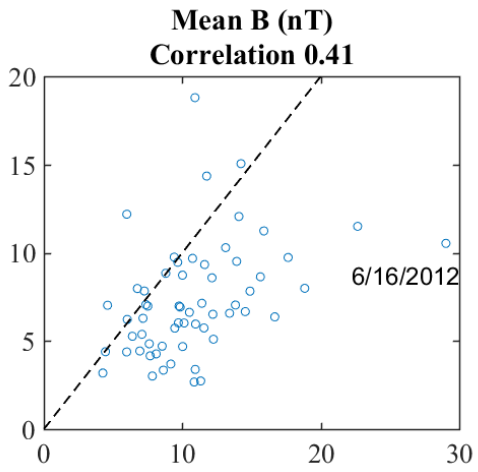
- ✓ As expected, the faster the predicted ICME speed than the observed speed, the earlier the ICME arrives at 1 AU than observed
- ✓ For **faster and stronger ICMEs**, their arrival time is generally better predicted

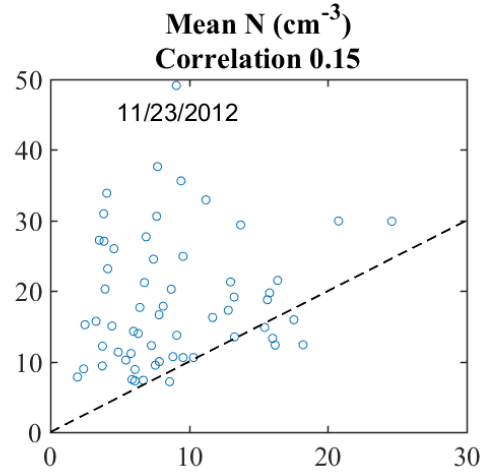
Simulated vs. Observed Mean Parameters of ICMEs

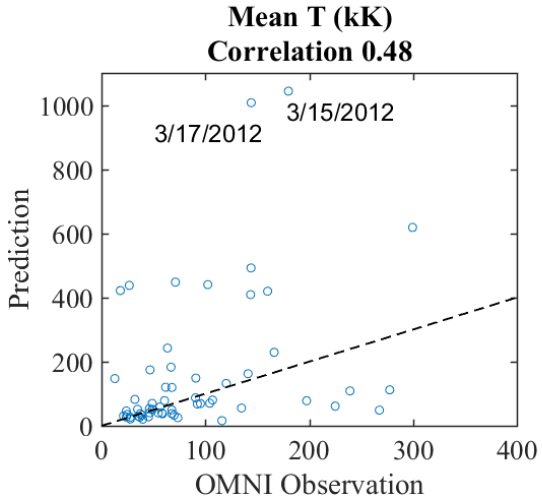
Improved

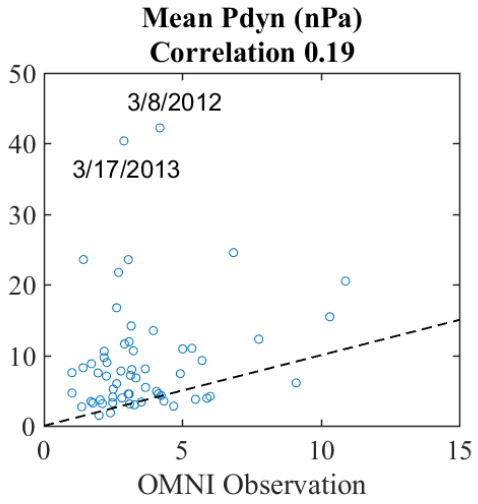


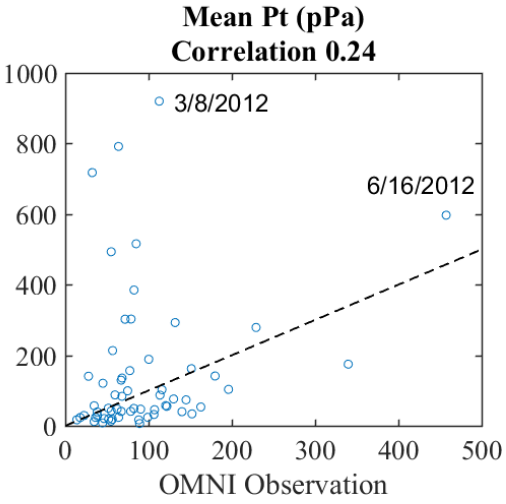
Improved











Summary and Discussion

- Comprehensive performance metrics are developed for solar wind prediction and are easy to adapt
- The inter-comparison of the models can be affected by their different grids, internal parameter settings, and inner boundary conditions
- The WSA-Enlil+Cone model is validated for long-term CME prediction. The results depend much on the model version and CME input parameter
- Statistically the prediction of the arrival time, ICME speed and magnetic field is improved but there is drawback in some other aspects
- We need to validate the modeling of a small number of CMEs which are well observed remotely and in situ. Well-calibrated CME parameters are highly needed!
- We need to include **internal magnetic field structures** in the Enlil model