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 Heliospheric 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

Jian et al. (2016)
### Introduction of the Model Description, Resolution, and Inner Boundary Condition

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>Resolution</th>
<th>Inner Boundary Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>WSA v2.2 coronal part, up to 21.5 Rs</td>
<td>PFSS+Schatten current sheet model, semiempirical Magnetogram with a smoothed resolution of 2.5° in latitude and longitude $101 \times 92 \times 182$ (radial $\times$ latitude $\times$ longitude) $\rightarrow$ (0.20 Rs, 2.0°, 2.0°)</td>
<td>Radial surface field, magnitude is set so that its line of sight component matches magnetogram</td>
<td></td>
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<tr>
<td>MAS v5.0 coronal part, up to 30 Rs</td>
<td>3-D MHD model, Polytropic Zero beta approximation Thermodynamic Full thermodynamic energy equation Magnetogram with a resolution of 1° in latitude and longitude $101 \times 101 \times 128$ $\rightarrow$ (0.29 Rs, 1.8°, 2.8°)</td>
<td>Base of corona: $T = 1.8$ MK and $N = 2 \times 10^{8}$ cm$^{-3}$ Chromosphere: $T = 0.02$ MK and $N = 2 \times 10^{12}$ cm$^{-3}$</td>
<td></td>
</tr>
<tr>
<td>Enlil heliospheric model, up to 430 Rs</td>
<td>3-D MHD model for super-Alfvénic solar wind, driven by WSA, MAS, and possible by other models too, only one temperature v2.8, coupling with WSA $1024 \times 120 \times 360$ $\rightarrow$ (0.40 Rs, 1.0°, 1.0°)</td>
<td>21.5 Rs: $V_{\text{slow}} = 200$ km/s, $V_{\text{fast}} = 700$ km/s, $T = 2$ MK, and $N = 200$ cm$^{-3}$</td>
<td></td>
</tr>
<tr>
<td>Enlil heliospheric model, up to 430 Rs</td>
<td>3-D MHD model for super-Alfvénic solar wind, driven by WSA, MAS, and possible by other models too, only one temperature v2.7, coupling with MAS $320 \times 60 \times 180$ $\rightarrow$ (1.25 Rs, 2.0°, 2.0°)</td>
<td>30 Rs: $V_{\text{slow}} = 250$ km/s, $V_{\text{fast}} = 650$ km/s, $T = 0.6$ MK, and $N = 150$ cm$^{-3}$</td>
<td></td>
</tr>
<tr>
<td>SWMF, 3-D MHD model, up to 500 Rs, separate ion and electron temperatures</td>
<td>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</td>
<td>Top of chromosphere: $T = 0.02$ MK and $N = 2 \times 10^{10}$ cm$^{-3}$</td>
<td></td>
</tr>
<tr>
<td>SWMF, 3-D MHD model, up to 500 Rs, separate ion and electron temperatures</td>
<td>Starting from the upper chromosphere, adding physics-based turbulent Alfvén 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)</td>
<td>Top of chromosphere: $T = 0.05$ MK and $N = 2 \times 10^{11}$ cm$^{-3}$</td>
<td></td>
</tr>
<tr>
<td>IPS tomography v15</td>
<td>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)</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

*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
Comparison of Solar Wind Speed at Earth Orbit in 2007

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

After Jian et al. (2015)
Capabilities of Capturing SIRs

(a) Rates of Hits & Misses (%)
(b) Rate of Correct & False Alarms (%)
(c) $\Delta t$ of Sl (day)
(d) $|\Delta t|$ of Sl (day)
(e) Ranking (8 for Best)

GONG - MAS v5.0 Poly - Enil v2.7
GONG - MAS v5.0 Thermo - Enil v2.7
GONG - SWMF v8.03
GONG - SWMF v9.20
GONG - WSA v2.2 - Enil v2.8f
GONG - WSA v2.2 - Enil v2.8f
MWO - WSA v2.2 - Enil v2.8f
NSO - WSA v2.2 - Enil v2.8f
GONG - IPS - Tomography v15

After Jian et al. (2015)
Capabilities of Capturing Latitudinal Variations of Solar Wind

Solar Wind Speed & IMF Polarity

Gong - WSA v2.2 - Enlil v2.8f

Gong - SWMF v8.03

Gong - MAS v5.0 Poly. - Enlil v2.7

MWO - WSA v2.2 - Enlil v2.8f

Gong - SWMF v9.20

Gong - MAS v5.0 Thermo. - Enlil v2.7

NSO - WSA v2.2 - Enlil v2.8f

Gong - IPS - Tomography

Jian et al. (2016)
## Summary of the Model Evaluation for 2007

<table>
<thead>
<tr>
<th>Synoptic Map</th>
<th>Model</th>
<th>Strength</th>
<th>Weakness</th>
</tr>
</thead>
<tbody>
<tr>
<td>MWO</td>
<td>WSA v2.2, Enlil v2.8</td>
<td>lowest RMSE for $N_p$ and $B$ &lt;br&gt; best match for low-latitude median $B$ and $T_p$, and high-latitude median $V$ &lt;br&gt; second highest correlation for $V$</td>
<td>underestimate the fast wind $V$ at middle to high latitudes</td>
</tr>
<tr>
<td>NSO/SOLIS</td>
<td>MAS v5.0, Enlil v2.7</td>
<td>lowest RMSE for $V$, normalized $V$, $N_p$, and $T_p$; highest correlation for $N_p$, $B$, and $T_p$ &lt;br&gt; second lowest RMSE for normalized $V$; second highest correlation for $N_p$, $B$, and $T_p$</td>
<td>N/A &lt;br&gt; underestimate the fast wind $V$ at middle to high latitudes; overestimate low-latitude median $N_p$ most; underestimate low-latitude median $B$ and $T_p$ most</td>
</tr>
<tr>
<td>GONG</td>
<td>SWMF v8.03</td>
<td>match low-latitude median $V$ best</td>
<td>largest RMSE for $N_p$, normalized $N_p$, $B$, and $T_p$; lowest correlation for $B$ and $T_p$</td>
</tr>
<tr>
<td></td>
<td>SWMF v9.20</td>
<td>capture the high-latitude hot solar wind well; lowest RMSE for $T_p$ and normalized $B$</td>
<td>latitudinal variations are much smoothed; produce north-south asymmetry not observed by Ulysses; largest RMSE for $V$</td>
</tr>
<tr>
<td></td>
<td>IPS Tomography v15</td>
<td>N/A</td>
<td>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</td>
</tr>
</tbody>
</table>

*Jian et al. (2016)*
Riley et al. (2014) showed the conversion factor between different observatories can be > 10, and it varies with latitude.
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
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° in latitude, and 360° 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°) 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
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 $\beta$, bidirectional suprathermal electron strahl, 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.
ICMEs in simulations are identified by requiring $D_p \geq 0.1$.

**ICME start time**
- The closest time when $V$ and/or $B$ increases sharply, earlier than $D_p \geq 0.1$
- 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 $D_p \geq 0.1$ or when solar wind parameters return to ambient, whichever comes last.
## Statistics of ICME Prediction in 2010-2016

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

- 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
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

Mean V (km/s)
Correlation 0.61

Mean B (nT)
Correlation 0.41

Mean N (cm$^{-3}$)
Correlation 0.15

Mean T (kK)
Correlation 0.48

Mean Pdyn (nPa)
Correlation 0.19

Mean Pt (pPa)
Correlation 0.24
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.