Validation of Solar and Heliospheric Models

P. MacNeice
(NASA/GSFC CCMC)

M. Hesse, M. Kuznetsova, L. Rastaetter, A. Taktakishvili
(CCMC)

CCMC Workshop, Jan. 28, 2010
Overview

• Ambient Model Validation
  – Goals of validation
  – Validation Procedure
  – Results
  – Conclusions
    • Semi-empirical/kinematic still better than MHD
    • Specific forecast probabilities
    • Validation process must be PRECISELY documented

• Cone Model Validation
• Future Plans
Solar/Helio Models at CCMC

- PFSS
- WSA (v1.6)
- WSA/ENLIL(V2.6)
- WSA/ENLIL+CONE
- CORHEL
  - 12 different combos (MAS-p, MAS-t, WSA*)/(MAS-p, MAS-t, ENLIL)
- SWMF (SC + IH)
- Heliospheric Tomography
  - Exospheric Solar Wind
  - ANMHD
  - Weigelmann NLFFF – coming soon(?) to support SDO.
Wang-Sheeley-Arge Model V1.6 (Arge)

• Time independent, semi-empirical model of corona and heliosphere

• Three Components
  – Source surface to 2.5$r_s$
  – Schatten current sheet from 2.5 to 5$r_s$
  – Kinematic solar wind from 5$r_s$ to 1AU

• Input: Photospheric synoptic magnetograms
  – Uses 72 harmonics (2.5° resolution)
  – We use Mt. Wilson, Kitt Peak and GONG
    • Data as far back as CR1650 (Jan 1978)

• Output:
  – Coronal magnetic field structure to 5$r_s$
  – Solar wind speed at 5$r_s$
  – Wind speed and $B_r$ polarity at 1AU
Wang-Sheeley-Arge Model V1.6 (Arge)

WSA tuned through formula for wind speed at 5 or 21.5\(r_s\)

\[
v(f_s, \theta_b) = a_1 + a_2 (1 + f_s)^{-a_3} (a_4 - a_5 e^{-(\theta_b/a_6)^{a_7}})^{a_8} \text{ km s}^{-1}
\]

Flux tube expansion rate relative to purely radial expansion

Proximity to nearest coronal hole boundary

eg. \(a_1=240 \text{ km.s}^{-1}, a_2=675 \text{ km.s}^{-1}, a_6=2.8^\circ\)
WSA/ENLIL V2.6 (Odstrcil)

- Time dependent Heliospheric 3D MHD
- Rotating inner boundary at 21.5\(r_s\)
- Based on WSA field and wind speed, *but*
  - Azimuthal field component added
  - Azimuthal offset added to allow for wind propagation time from 1 to 21.5\(r_s\)
  - \(v \rightarrow (v - 50)\) km.s\(^{-1}\), with floor of 250 km.s\(^{-1}\) and ceiling of 650 km.s\(^{-1}\)
  - \(n v^2 = 300 \times 650^2\) (constant KE)
  - \(n T = 300 \times 0.8\) (constant pressure)
- Outer boundary at 2AU
- Can run ambient or cone model cases
Goals of Validation

• Establish an ongoing validation program applicable to the general class of models
  – Semi-automated for efficiency when applied to new or upgraded models
• Determine which models give best forecasts for observables of interest?
• Quantify their prediction performance
• Measure progress toward better first principles models
• Provide feedback to model developers and funding agencies
Validation Procedure

- Establish WSA as ‘baseline’ model
  - Validate ‘baseline’ against persistence and mean models
  - Validate other models against WSA
- Closely follows model developers validation strategies (Owens et al, 2005)
  - Added testing of IMF polarity
- Use all available archived synoptic maps from MWO, NSO and GONG
  - Larger database than Owens et al
- Two measures
  1. Skill scores
     - Focused on ‘persistence’ rather than ‘mean’ as reference model
  2. Event detection
     - Characterize 24 hour forecast accuracy
WSA Skill Scores

Standardized definition (Brier, 1950)

\[ D^A_F = \frac{1}{N} \sum_{i=1}^{N} (F^A_m(i) - F_o(i))^2. \]

\[ M^{AB}_F = 1 - \frac{D^A_F}{D^B_F}. \]

Sun rotates through 2.5° in 4.5 hours, so we used this as our time bin size.
• For both wind speed and IMF polarity, WSA is
  - not as good as 1 day persistence
  - slightly better than 2 day persistence
  - better than 4 or 8 day persistence
• Large scatter in skill score results between CRs and sometimes for same CR with different observatory
• Nevertheless overall average skill scores are insensitive to different magnetogram sources
• No significant difference in skill scores between quiet and active periods

<table>
<thead>
<tr>
<th></th>
<th>Wind Speed</th>
<th>B_z Polarity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NSO</td>
<td>MWO</td>
</tr>
<tr>
<td>Reference Model Persistence (1 day)</td>
<td>0.77</td>
<td>0.77</td>
</tr>
<tr>
<td>Persistence (2 days)</td>
<td>0.27</td>
<td>0.27</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Velocity</th>
<th>B_z Polarity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Quiet</td>
<td>Active</td>
</tr>
<tr>
<td>Reference Model Persistence (1 day)</td>
<td>1.10</td>
<td>0.87</td>
</tr>
<tr>
<td>Persistence (2 days)</td>
<td>0.04</td>
<td>0.03</td>
</tr>
</tbody>
</table>

* MacNeice, P., 2009, *Space*
Why it is a good idea to come to the CCMC Workshop!

WSA vs 27.27 day persistence

Caveat: Haven’t had a chance to thoroughly check out the mods to the analysis software!
WSA Event Detection

High Speed Events

- Tweaked Owens et al definition of HSE thresholds

IMF $B_r$ Polarity
WSA Event Detection

**WSA (GONG, NSO, MWO average)**

<table>
<thead>
<tr>
<th></th>
<th><strong>HSE</strong></th>
<th><strong>$B_r$, Polarity</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hit Rate</td>
<td>39%</td>
<td>Hit Rate 61%</td>
</tr>
<tr>
<td>Miss Rate</td>
<td>61%</td>
<td>Miss Rate 39%</td>
</tr>
<tr>
<td>False Positive</td>
<td>39%</td>
<td>False Positive Rate 11%</td>
</tr>
<tr>
<td></td>
<td>Rate</td>
<td>IMF Polarity correct 76% of time.</td>
</tr>
</tbody>
</table>

IMF Polarity correct 76% of time.
# WSA Event Detection

## 24 Hour Forecast Probabilities

<table>
<thead>
<tr>
<th>WSA predicts HSE</th>
<th>OMNI HSE</th>
<th>No OMNI HSE</th>
<th>OMNI HSE</th>
<th>No OMNI HSE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GONG</td>
<td>MWO</td>
<td>NSO</td>
<td>Wt. Aver.</td>
</tr>
<tr>
<td>WSA predicts HSE</td>
<td>23</td>
<td>15</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>No OMNI HSE</td>
<td>77</td>
<td>85</td>
<td>83</td>
<td>83</td>
</tr>
<tr>
<td>WSA predicts no HSE</td>
<td>10</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>No OMNI HSE</td>
<td>90</td>
<td>94</td>
<td>94</td>
<td>94</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Current Polarities</th>
<th>WSA predicts revers.</th>
<th>WSA predicts no revers.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OMNI revers.</td>
<td>OMNI revers.</td>
</tr>
<tr>
<td></td>
<td>36 9 31 6 33 6</td>
<td>64 91 69 94 67 94</td>
</tr>
<tr>
<td></td>
<td>32 6</td>
<td>68 94</td>
</tr>
<tr>
<td></td>
<td>7 37 7 29 7 29</td>
<td>7 29</td>
</tr>
<tr>
<td></td>
<td>93 63 93 71 93 71</td>
<td>93 71</td>
</tr>
<tr>
<td></td>
<td>93 71</td>
<td>93 71</td>
</tr>
</tbody>
</table>
Comparison of results with those of the model developers suggest:

• Importance of precise specification of event detection algorithms, particularly with regard to data binning, data rejection criteria
• Owens et al description appears straightforward, but results were not reproducible without collaboration with author.
• Affected absolute forecast probabilities, not relative measures of model performance
• Emphasizes need for one consistent evaluation of all models
WSA/ENLIL Skill Scores

- Full NSO archive
- 256x60x180 – 2° resolution
- Average skill scores
  - Velocity -0.7
  - IMF Polarity -0.15
WSA/ENLIL Skill Scores

- GONG magnetograms
- 3 resolutions
  - Low 128x30x90 – 4°
  - Med 256x60x180 – 2°
  - High 512x120x360 – 1°
- Average skill scores
  - Velocity -0.12 / -0.16 / -0.76
  - IMF Polarity -0.47 / -0.37 / -0.42
- No justification for higher resolution for ENLIL’s grid
Ambient Wind - Conclusions

- WSA alone is slightly better than 2 day persistence
- WSA/ENLIL not yet as good as WSA only
  - Improve specific WSA tuning for WSA/ENLIL runs
  - Implication that main wind structures at 1AU are imprinted by $21.5r_s$ and improvements need better coronal models (?)
  - Medium resolution ENLIL (matched to WSA resolution) gives best skill scores (marginally)
- Results consistent with model developers validations, except that ‘event’ forecasts are not as good
Cone Model Validation (Taktakishvili)

Zhao et al, 2002, Cone Model - iterative method:
- CME propagates with nearly constant angular width in a radial direction
- The source is near the solar disc center
- CME bulk velocity is radial and the expansion is isotropic

Xie et al, 2004, Cone Model for Halo CMEs — analytical method:
- The projection of the cone on the POS is an ellipse

Baseline approximation to describe halo CME
Example: Fall AGU Dec 2006 storm CME

Parameters derived from the images – input to ENLIL

- Latitude of the cone axis
- Longitude of the cone axis
- \( r \) – angular width
- \( v_r \) – radial velocity

One additional parameter used as input for the WSA/ENLIL cone model that cannot be derived from the observations is the

**Density Factor** –

the ratio of density of the CME cloud to ambient plasma density
We modeled 14 halo CMEs chosen from the catalogue (http://cdaw.gsfc.nasa.gov/CME_list), using the following criteria:  
1) clear LASCO/C3 images to enable better determination of cone model parameters:  
2) clear shock arrival time observed by ACE, to facilitate comparison with the observations;  
3) estimated initial plane of sky velocities > 700 km/s.  

We studied:  

- **CME arrival time** prediction  
- **Magnitude** of impact

<table>
<thead>
<tr>
<th>EVENT #</th>
<th>CME start date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>August 9, 2000</td>
</tr>
<tr>
<td>2</td>
<td>March 29, 2001</td>
</tr>
<tr>
<td>3</td>
<td>April 6, 2001</td>
</tr>
<tr>
<td>4</td>
<td>October 9, 2001</td>
</tr>
<tr>
<td>5</td>
<td>November 17, 2001</td>
</tr>
<tr>
<td>6</td>
<td>March 18, 2002</td>
</tr>
<tr>
<td>7</td>
<td>April 15, 2002</td>
</tr>
<tr>
<td>8</td>
<td>April 17, 2002</td>
</tr>
<tr>
<td>9</td>
<td>August 16, 2002</td>
</tr>
<tr>
<td>10</td>
<td>August 24, 2002</td>
</tr>
<tr>
<td>11</td>
<td>October 28, 2003</td>
</tr>
<tr>
<td>12</td>
<td>October 29, 2003</td>
</tr>
<tr>
<td>13</td>
<td>July 25, 2004</td>
</tr>
<tr>
<td>14</td>
<td>December 13, 2006</td>
</tr>
</tbody>
</table>
Comparison to $v_{\text{const}} = 850 \text{ km/s}$ and Empirical Shock Arrival (ESA) Models

<table>
<thead>
<tr>
<th>Reference Model 1</th>
<th>Reference Model 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(constant velocity propagation):</td>
<td>ESA Model (Gopalswamy et al):</td>
</tr>
<tr>
<td>Propagation with the average of Halo</td>
<td>Model predicting CME shock arrival time based on an</td>
</tr>
<tr>
<td>CME initial velocities (from the CME</td>
<td>empirical relationship between CME initial speed $u$</td>
</tr>
<tr>
<td>catalogue, years 1996-2006)</td>
<td>and its acceleration $a$</td>
</tr>
<tr>
<td>$v=850 \text{ km/s}$</td>
<td>$a = 2.193 - 0.0054 , u$</td>
</tr>
<tr>
<td>Average propagation time to the ACE</td>
<td>Average propagation time to the ACE</td>
</tr>
<tr>
<td>satellite:</td>
<td>satellite:</td>
</tr>
<tr>
<td>$T(\text{prop}) \sim 48 \text{ hours}$</td>
<td>$T(\text{prop}) \sim \text{varies}$</td>
</tr>
</tbody>
</table>
CME Shock Arrival Time Prediction Metrics

\[ R = 1 - \frac{|\Delta t_{\text{arr}}^{\text{enlil}}|}{|\Delta t_{\text{arr}}^{\text{ref.m}}|} \]

WSA/ENLIL: avg. \( |\Delta t_{\text{err}}| \): \( \sim 5.9 \text{h} \)

\( v=850 \): avg. \( |\Delta t_{\text{err}}| \): \( \sim 10.9 \text{h} \)

ESA: avg. \( |\Delta t_{\text{err}}| \): \( \sim 8.4 \text{h} \)

WSA/ENLIL does better job in 9(8) cases (out of 14) with respect to \( v=850 \text{ km/s} \) (ESA) models
Magnitude of CME Impact on the Magnetosphere

Magnetic field required to stop SW

\[ \frac{B_{stop}^2}{2\mu_0} = Knm_p V^2 \]

Magnetopause standoff distance

\[ \frac{r_{mp}}{R_e} = \left( \frac{B_0}{B_{stop}} \right)^{1/3} \]

Example: December 13, 2006 CME
Magnitude of CME Impact on the Magnetosphere

$B_{\text{max}}$ and $r_{mp}^{\text{min}}$ for 14 studied events

WSA/ENLIL overestimates the magnitude of the CME impact on the magnetosphere: the predicted magnetopause standoff distance is smaller than distance corresponding to the observations.
Uncertainty Estimation: Dependence of the Arrival Time Error on Velocity, Density Factor and Radius

Example: December 13, 2006 CME “high” speed CME

The observed CME transit time for this event was 35 hours;
Largest uncertainty window: [-8,+8] hours

Arrival time error depends:

(1) most of all on cloud initial velocity,
(2) less on cone radius,
(3) least on density factor.
Cone Model Validation Summary

- Studied 14 CME events and comparing model results to the ACE satellite observations;
- The model performs better than reference / empirical model for the shock arrival times in 64% / 57% of the cases.
- The model predicts shock arrival earlier than observed arrival in 64% of the cases, versus 36% for later arrival prediction. Early arrival prediction errors are on the average larger than late prediction errors.
- The model overestimates the CME impact on the magnetosphere: the predicted magnetopause standoff distance is smaller than distance corresponding to the observations.
- Arrival time error depends most of all on a cloud initial velocity, less on cone radius and least on density factor.
- The strength of a CME impact on the magnetosphere depends most of all on cone radius (the total mass that carries CME?), less on initial velocity and least on a density factor.
Future Plans

- Extending Ambient model Validation
  - Add event analysis for WSA/ENLIL
  - CORHEL V4
  - SWMF
- Fieldline Tracing
  - Study in progress – Brian Elliott (USAF Acad.)
• Plan to test
  – MAS-p/ENLIL
  – MAS-p/MAS-p
  – WSA-C/ENLIL

• Issues
  – What convergence requirements to use for MAS?
Caveat: Need to do careful double-checking of these results!
Caveat: Need to do careful double-checking of these results!
SWMF

- Infrastructure Built
- Need to do common sense skill score checking
- Issues
  - How to characterize grid resolution when comparing with reference model?

Will be adding WSA shortly
Validating Fieldline Tracing

- Identify impulsive SEP events at 1AU with clear timing association with surface event
- Trace from Earth location to surface through model solutions
- Study in progress – Brian Elliott (USAF Acad.)
- Existing event catalogs are seriously flawed
  - Some SEPs arrive too soon
  - Some have clearer associations to other surface events
  - Some SEPs are interplanetary, not surface related
- From catalogs of more than 1000 events, we have identified ~ 20 ‘good’ candidates
- **Preliminary indications** that simple ‘potential corona + spiral IMF’ outperforms WSA+Spiral or WSA/ENLIL
Validation Publications

Taktakishvili et al, 2010, submitted to *Space Weather*