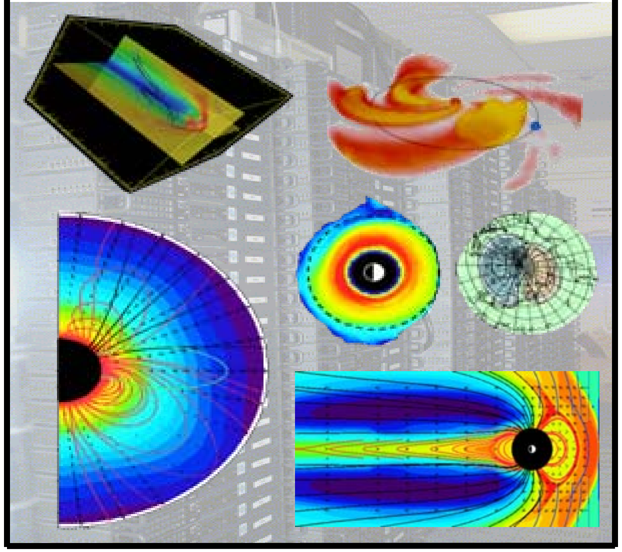
Community
Coordinated
Modeling
Center

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

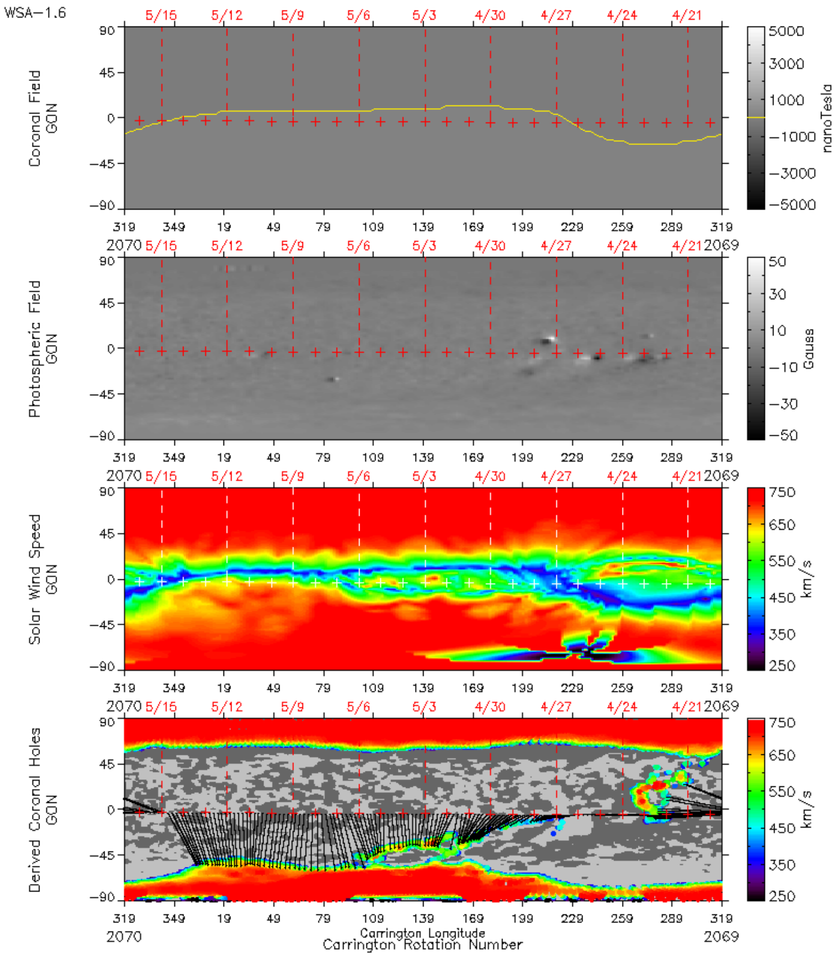
- Ambient Model Validation
  - Goals of validation
  - Validation Procedure
  - Results
  - Conclusions
    - Semi-empirical/kinematic still better than MHD
    - Specific forecast probabilities
    - Validation process must be PRECISELY documented
- Cone Model Validation
- Future Plans

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 2.5r_s
  - Schatten current sheet from 2.5 to 5r_s
  - Kinematic solar wind from 5r_s to 1AU
- Input: Photospheric synoptic magnetograms
  - Uses 72 harmonics (2.5^o resolution)
  - We use Mt. Wilson, Kitt Peak and GONG
    - Data as far back as CR1650 (Jan 1978)
- Output:
  - Coronal magnetic field structure to 5r_s
  - Solar wind speed at 5r_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 21.5r_s

$$\boxed{v(f_s,\theta_b) = a_1 + a_2(1+f_s)^{-a_3}\left(a_4 - a_5\, e^{-(\theta_b/a_6)^{a_7}}\right)^{a_8} \qquad \mathrm{km\ s^{-1}}}$$

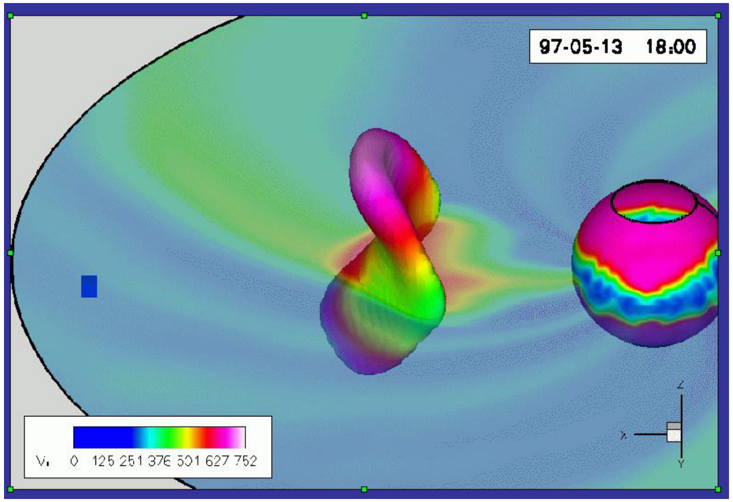
Flux tube expansion rate relative to purely radial expansion

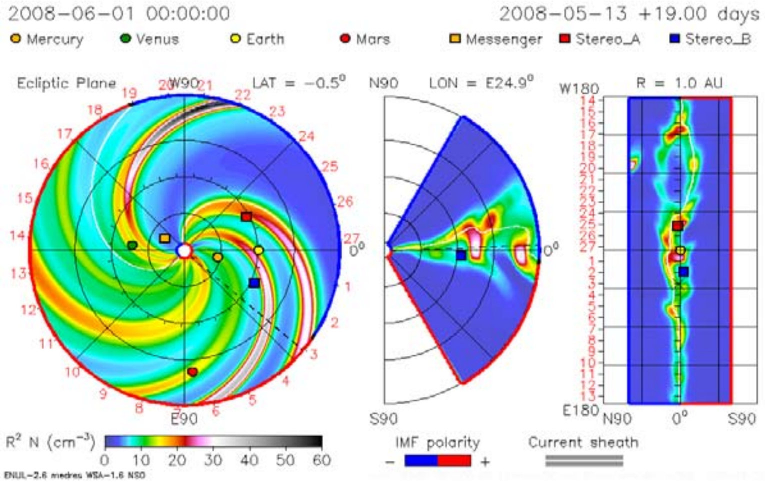
Proximity to nearest coronal hole boundary

eg. a_1=240 km.s^{-1}, a_2=675 km.s^{-1}, a_6=2.8^{o}

WSA/ENLIL V2.6 (Odstrcil)

- Time dependent Heliospheric 3D MHD
- Rotating inner boundary at $21.5r_s$
- Based on WSA field and wind speed, *but*
  - Azimuthal field component added
  - Azimuthal offset added to allow for wind propagation time from 1 to $21.5r_s$
  - $v \longrightarrow (v - 50)$ 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

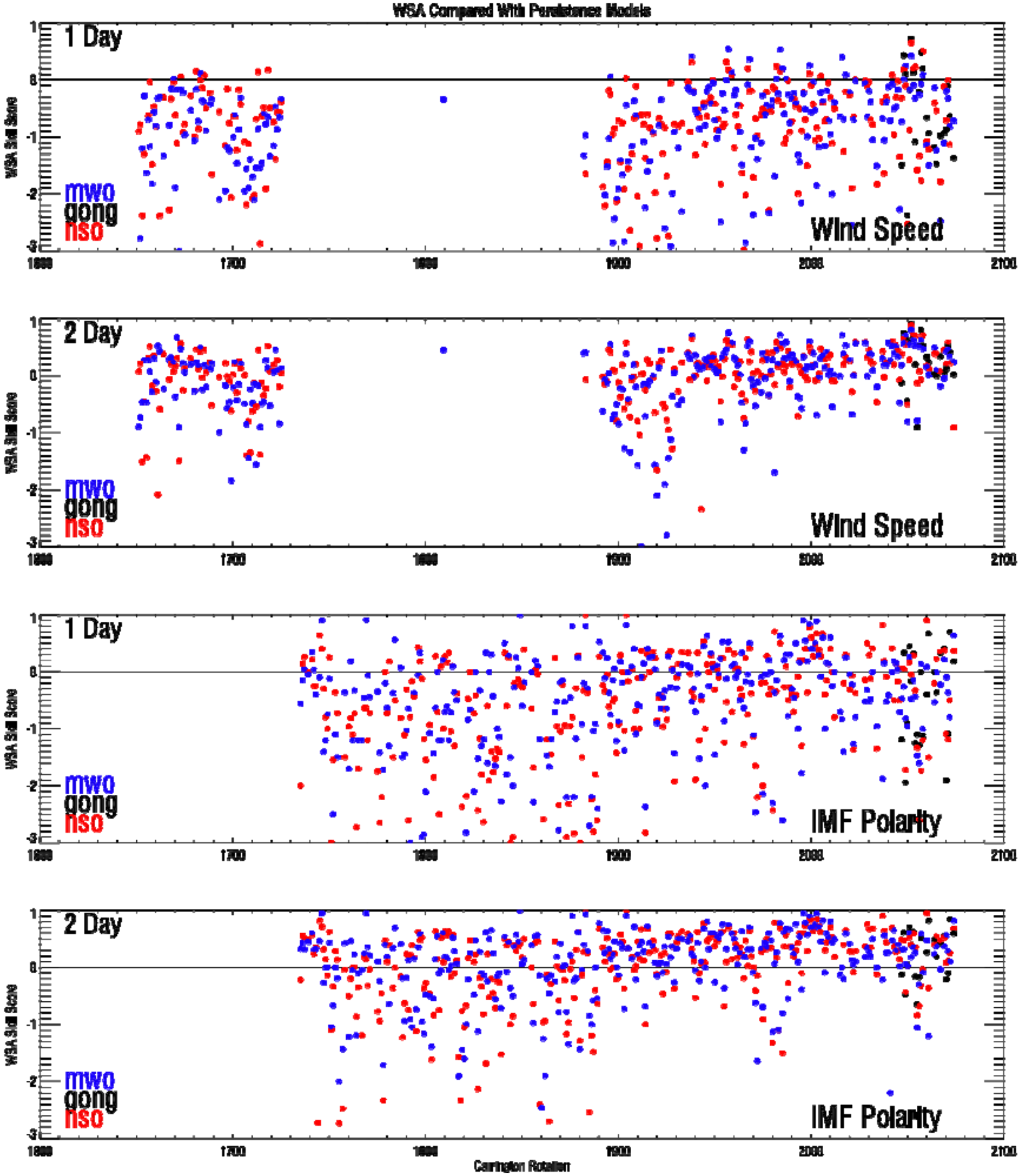
WSA Skill Scores

Standardized definition (Brier, 1950)

$$D_F^A = \frac{1}{N}\sum_{i=1}^{N}(F_m^A(i) - F_o(i))^2.$$

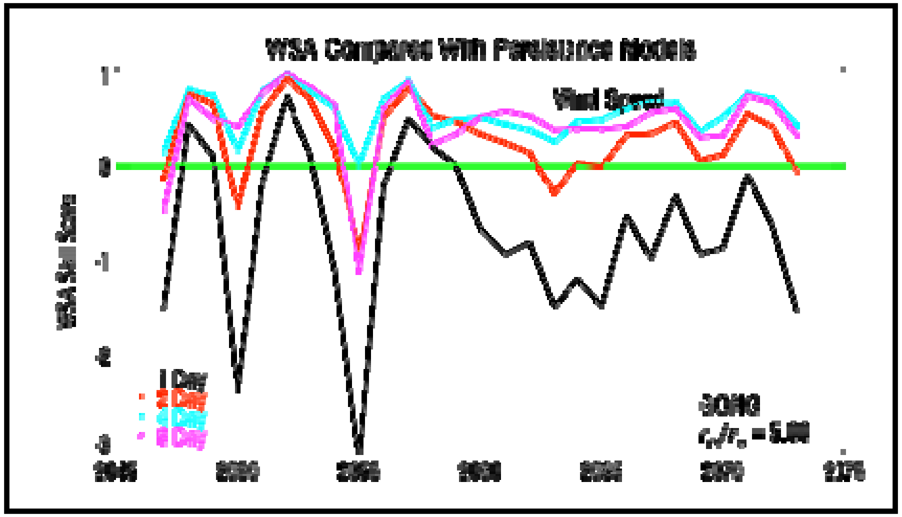
$$M_F^{AB} = 1 - \frac{D_F^A}{D_F^B}.$$

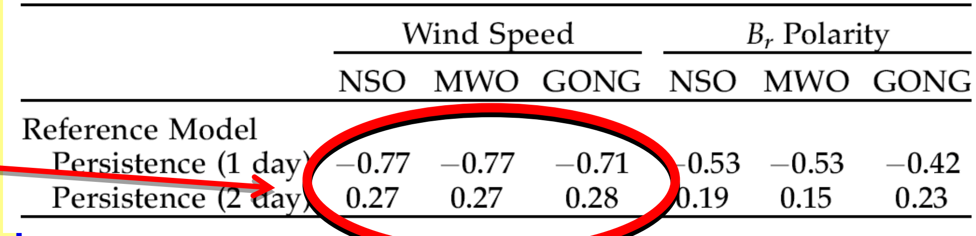
Sun rotates through 2.5° in 4.5 hours, so we used this as our time bin size.



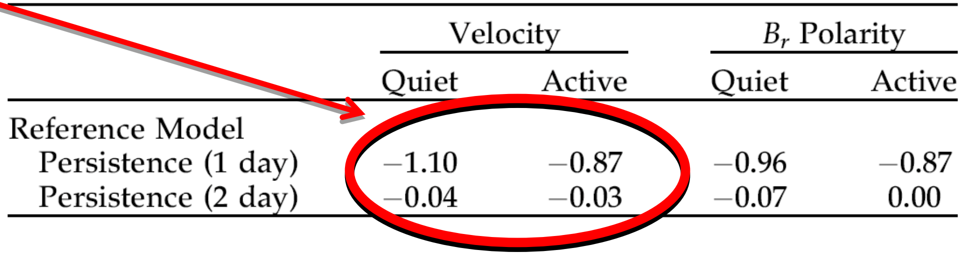
WSA Skill Scores*

- 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





	Wind Speed			B_r Polarity		
	NSO	MWO	GONG	NSO	MWO	GONG
Reference Model						
Persistence (1 day)	−0.77	−0.77	−0.71	−0.53	−0.53	−0.42
Persistence (2 day)	0.27	0.27	0.28	0.19	0.15	0.23

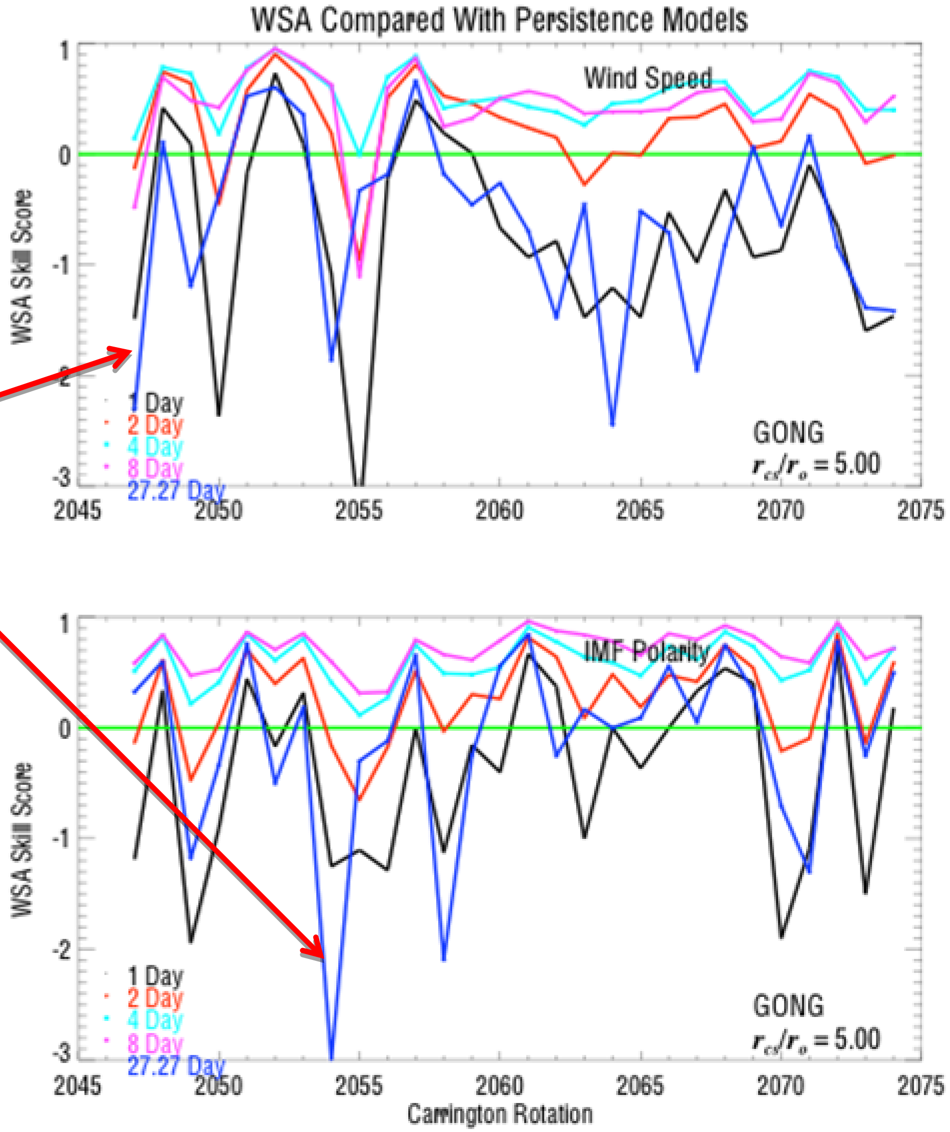


	Velocity		B_r Polarity	
	Quiet	Active	Quiet	Active
Reference Model				
Persistence (1 day)	−1.10	−0.87	−0.96	−0.87
Persistence (2 day)	−0.04	−0.03	−0.07	0.00

* MacNeice,P., 2009, *Space*

Why it is a good idea to come to the CCMC Workshop!

WSA vs 27.27 day persistence

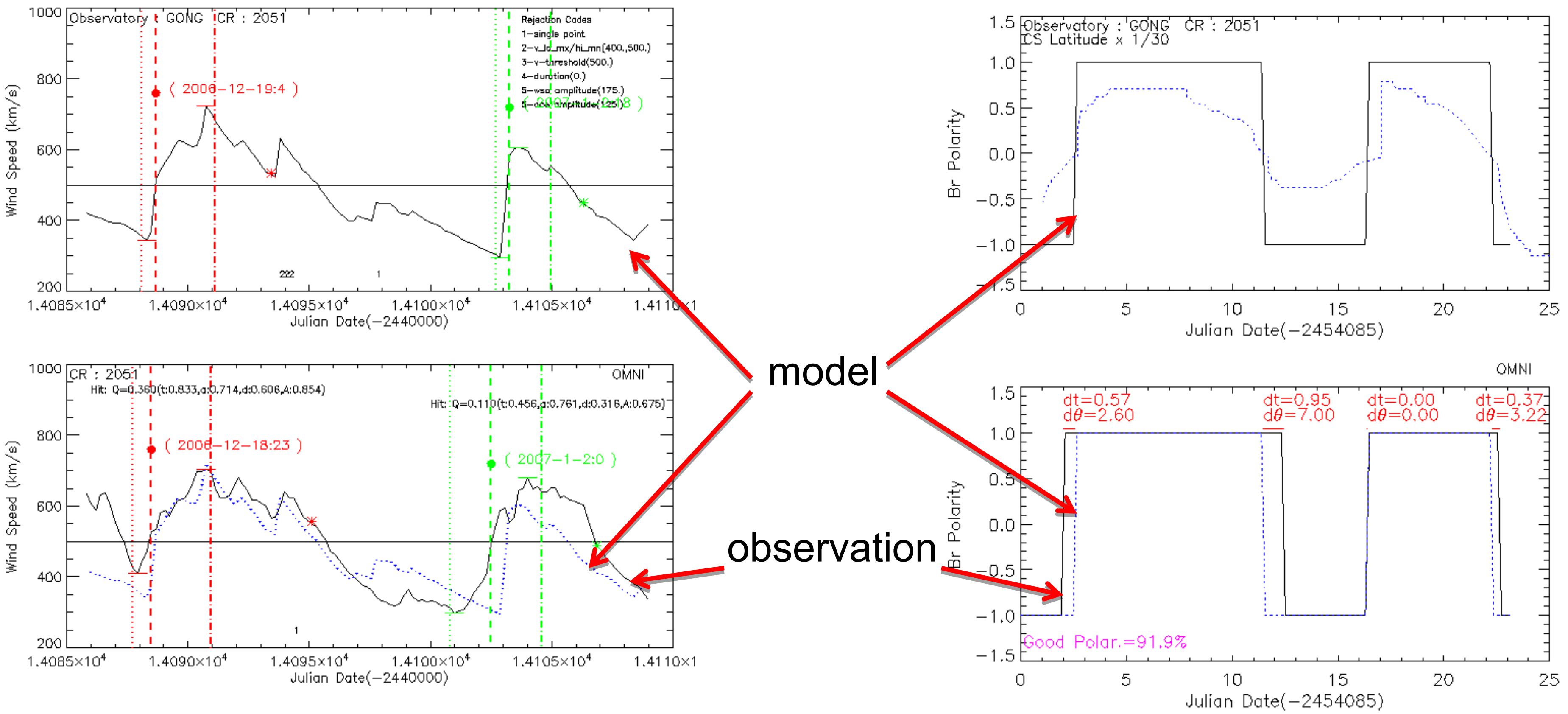


Caveat: Haven't had a chance to thoroughly check out the mods to the analysis software!

WSA Event Detection

High Speed Events

IMF B_r Polarity



model

observation

- Tweaked Owens et al definition of HSE thresholds
- Details - MacNeice, 2009, *Space Weather*,**7**,6.

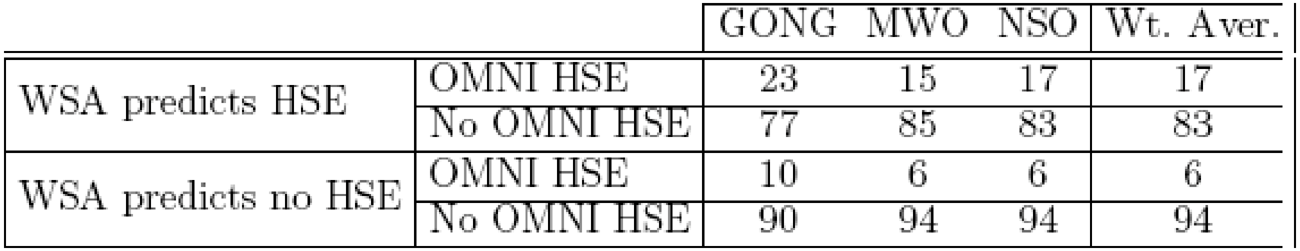
WSA Event Detection

WSA (GONG,NSO,MWO average)

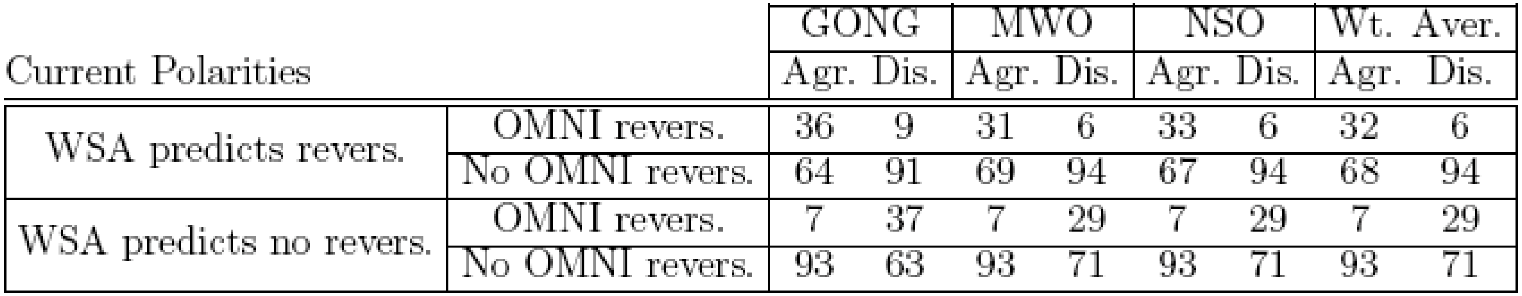
HSE	***B_r* Polarity**
Hit Rate 39%	Hit Rate 61%
Miss Rate 61%	Miss Rate 39%
False Positive Rate 39%	False Positive Rate 11%
	IMF Polarity correct 76% of time.

WSA Event Detection

24 Hour Forecast Probabilities



		GONG	MWO	NSO	Wt. Aver.
WSA predicts HSE	OMNI HSE	23	15	17	17
	No OMNI HSE	77	85	83	83
WSA predicts no HSE	OMNI HSE	10	6	6	6
	No OMNI HSE	90	94	94	94



		GONG		MWO		NSO		Wt. Aver.	
Current Polarities		Agr.	Dis.	Agr.	Dis.	Agr.	Dis.	Agr.	Dis.
WSA predicts revers.	OMNI revers.	36	9	31	6	33	6	32	6
	No OMNI revers.	64	91	69	94	67	94	68	94
WSA predicts no revers.	OMNI revers.	7	37	7	29	7	29	7	29
	No OMNI revers.	93	63	93	71	93	71	93	71

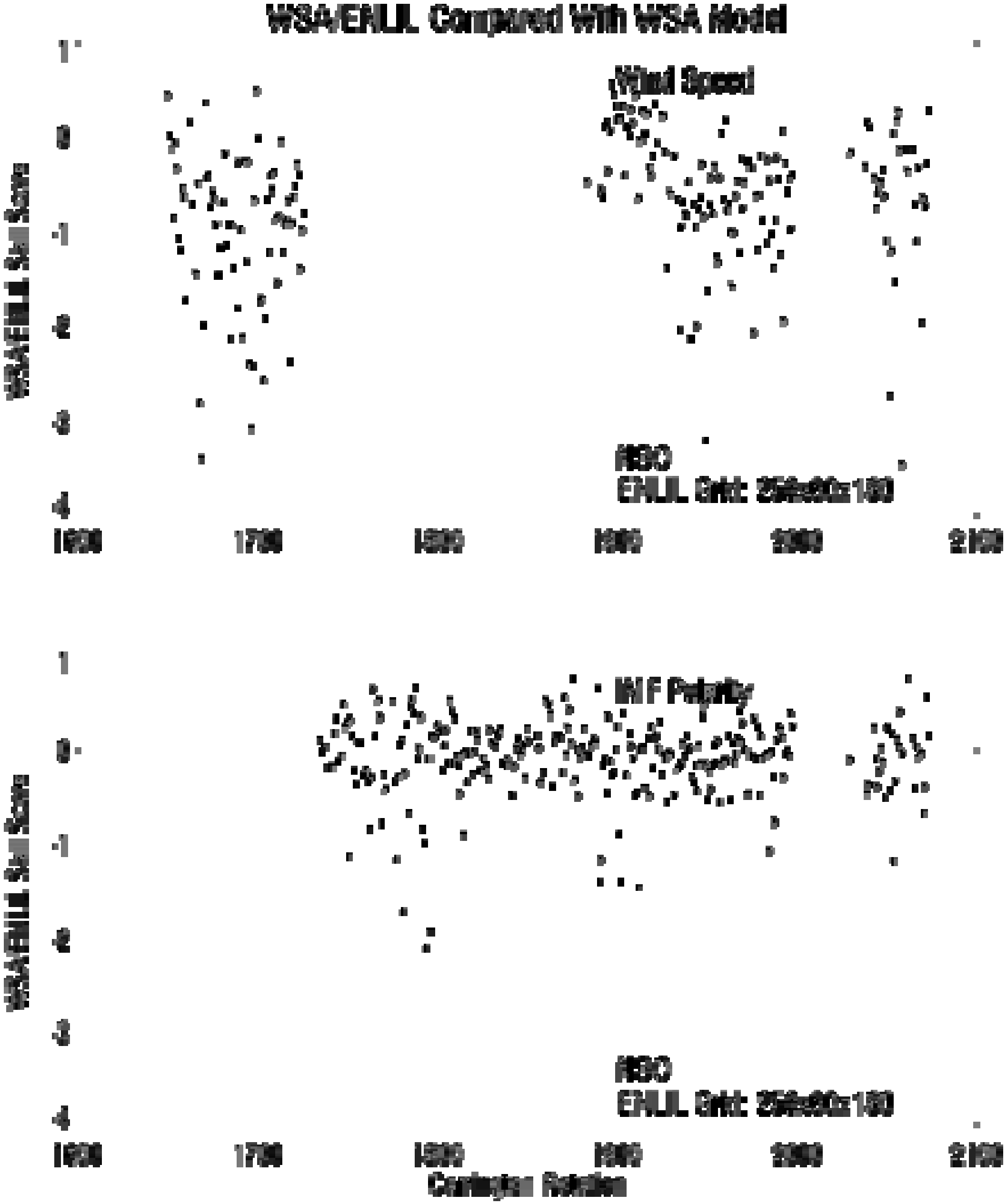
Procedure Definitions

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

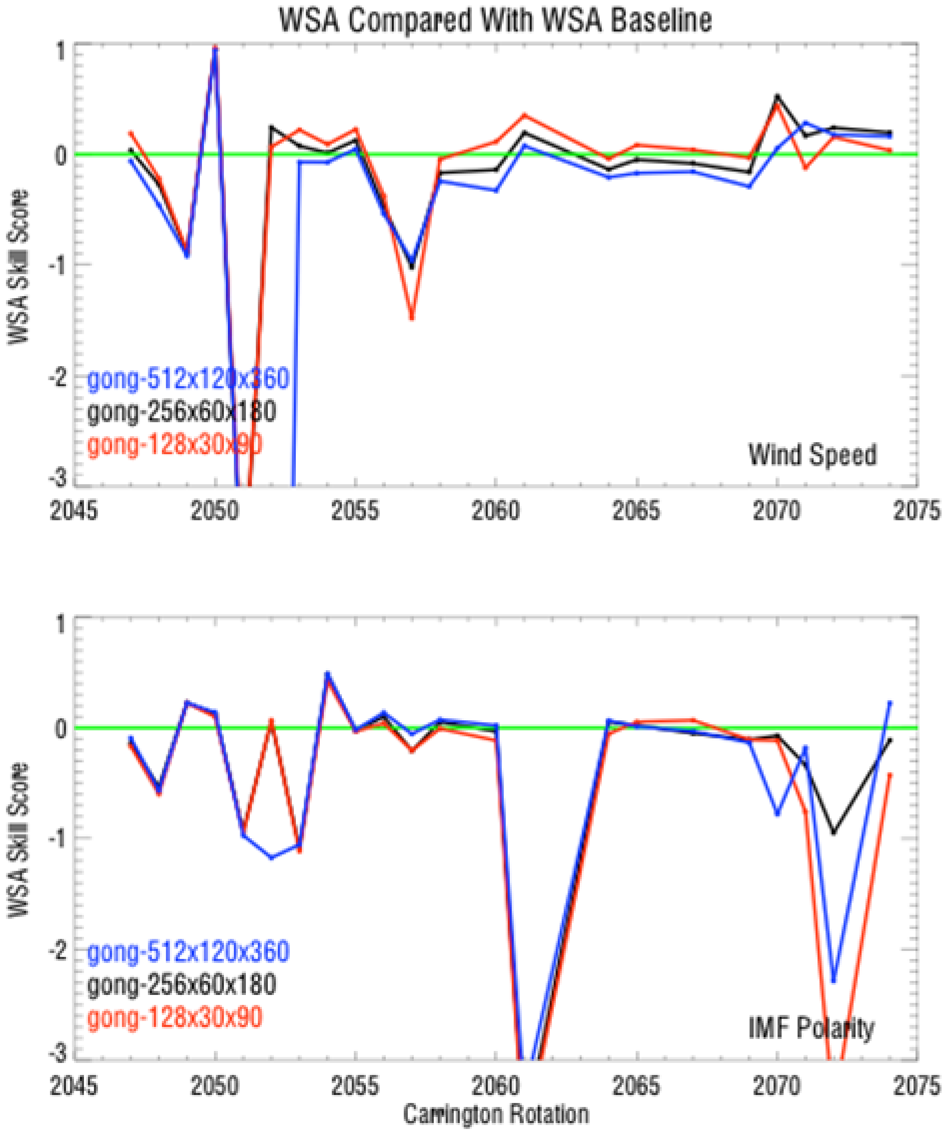
WSA/ENLIL Skill Scores

- Full NSO archive
- 256x60x180 – 2° resolution
- Average skill scores
  - Velocity -0.7
  - IMF Polarity -0.15



WSA/ENLIL Skill Scores

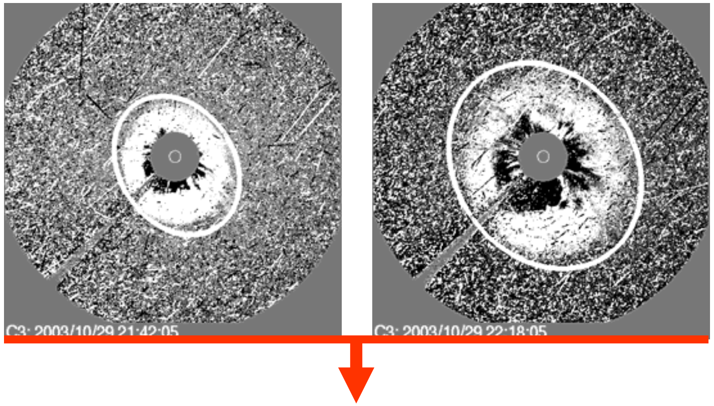
- GONG magnetograms
- 3 resolutions
  - Low 128x30x90 – 4°
  - Med 256x60x180 – 2°
  - High 512x120x360 – 1°
- Average skill scores
  - Velocity -0.12 / -0.16 / -0.76
  - IMF Polarity -0.47 / -0.37 / -0.42
- No justification for higher resolution for ENLIL's grid

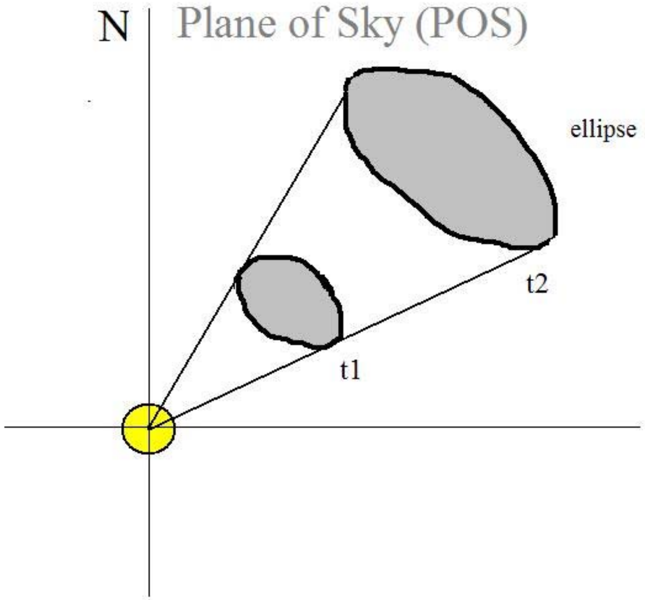


Ambient Wind - Conclusions

- 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

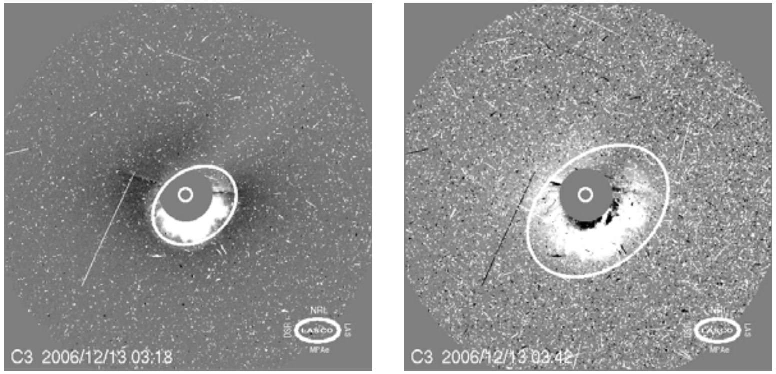
Xie et al, 2004, Cone Model for Halo CMEs – analytical method:

The projection of the cone on the POS is an ellipse

Baseline approximation to describe halo CME

Example: Fall AGU Dec 2006 storm CME

LASCO/C3 running difference images



Parameters derived from the images – input to ENLIL

Latitude of the cone axis
Longitude of the cone axis

radius – angular width

v_r- radial velocity

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

Density Factor –

the ratio of density of the CME cloud to ambient plasma density

Studied Events

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

EVENT #	CME start date
1	August 9, 2000
2	March 29, 2001
3	April 6, 2001
4	October 9, 2001
5	November 17, 2001
6	March 18, 2002
7	April 15, 2002
8	April 17, 2002
9	August 16, 2002
10	August 24, 2002
11	October 28, 2003
12	October 29, 2003
13	July 25, 2004
14	December 13, 2006

Comparison to v_{const}= 850 km/s and Empirical Shock Arrival (ESA) Models

Reference Model 1

(constant velocity propagation):

Propagation with the average of Halo CME initial velocities (from the CME catalogue, years 1996-2006)

$\boldsymbol{v}$**=850 km/s**

Average propagation time to the ACE satellite:

$\boldsymbol{T}$**(prop) ~ 48 hours**

Reference Model 2

ESA Model (Gopalswamy et al):

Model predicting CME shock arrival time based on an empirical relationship between CME initial speed ***u*** and its acceleration ***a***

$$\boldsymbol{a = 2.193 - 0.0054\, u}$$

Average propagation time to the ACE satellite:

$\boldsymbol{T}$**(prop) ~ varies**

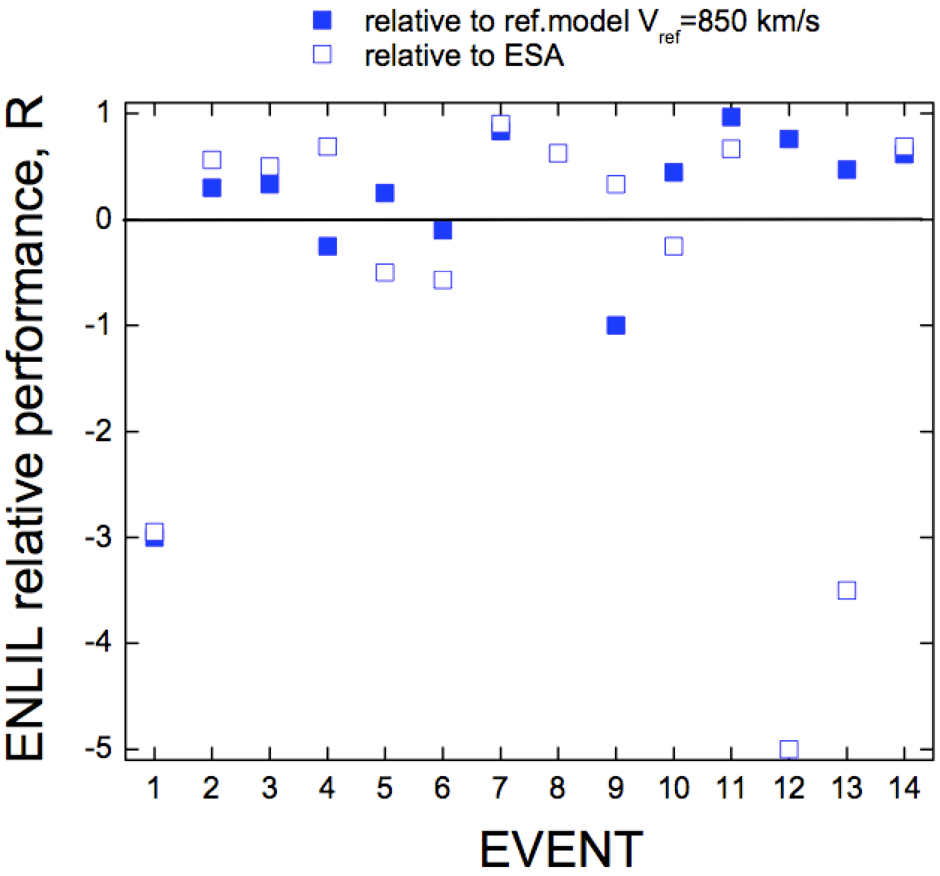
CME Shock Arrival Time Prediction Metrics

$$R = 1 - \frac{\left|\Delta t^{arr}_{enlil}\right|}{\left|\Delta t^{arr}_{ref.m}\right|}$$

WSA/ENLIL: avg. $|\Delta t_{err}|$: **~ 5.9h**

v=850: avg. $|\Delta t_{err}|$: **~ 10.9 h**

ESA: avg. $|\Delta t_{err}|$: **~ 8.4 h**



WSA/ENLIL does better job in 9(8) cases (out of 14) with respect to v=850 km/s (ESA) models

Magnitude of CME Impact on the Magnetosphere

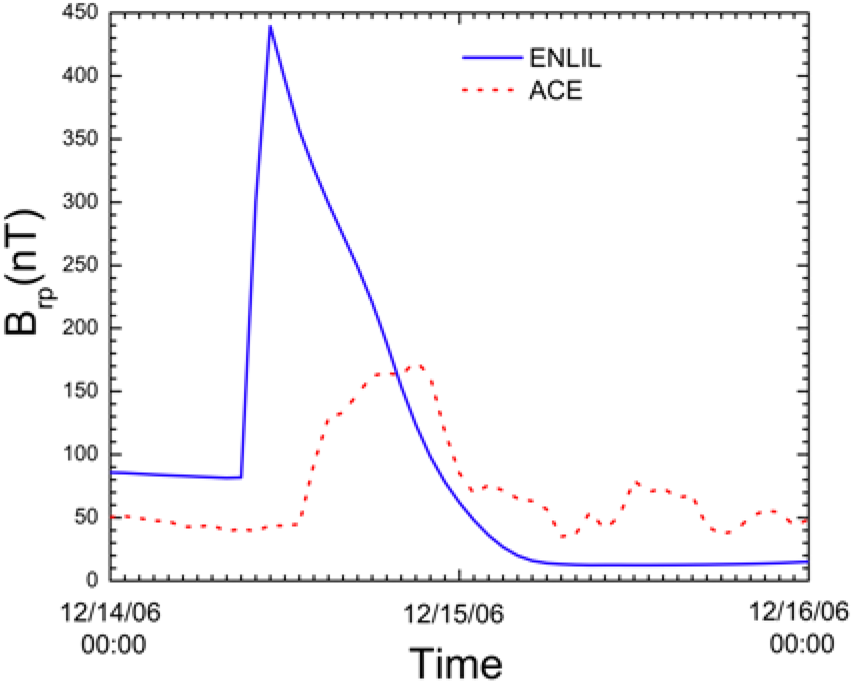
Magnetic field
required
to stop SW

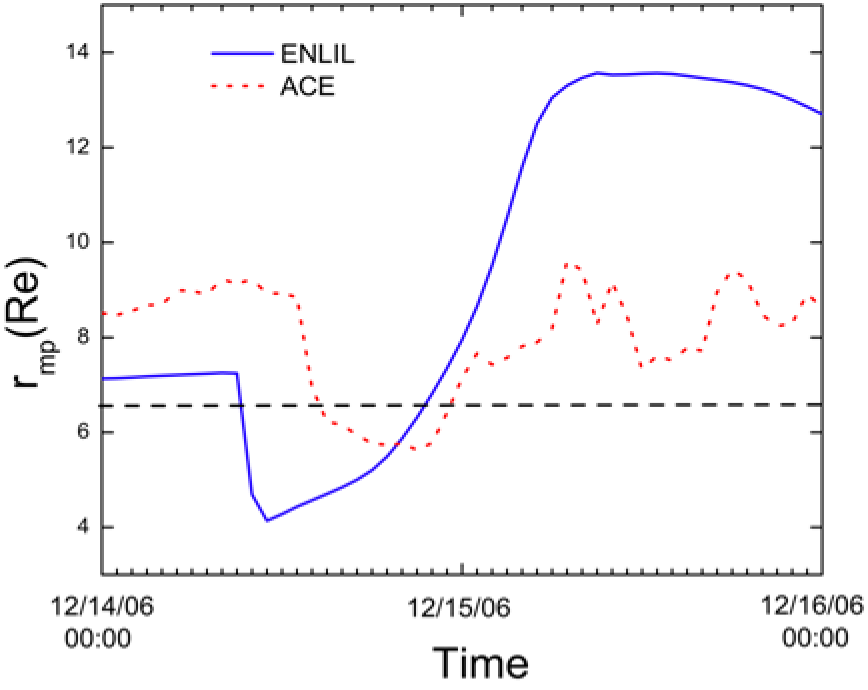
$$\frac{B_{stop}^2}{2\mu_0} = Knm_pV^2$$

Magnetopause
standoff
distance

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

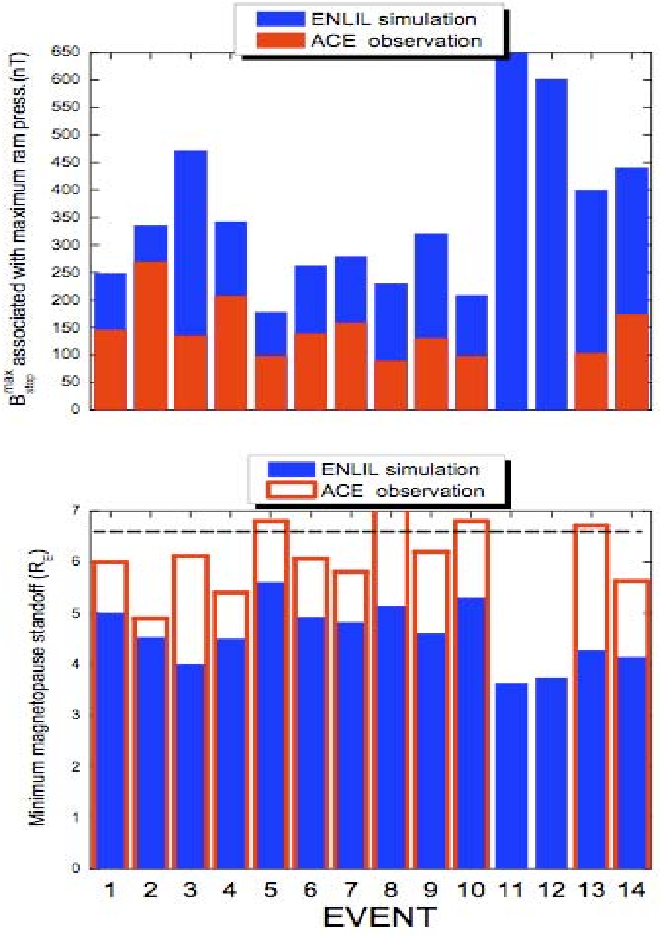
Example: December 13, 2006 CME





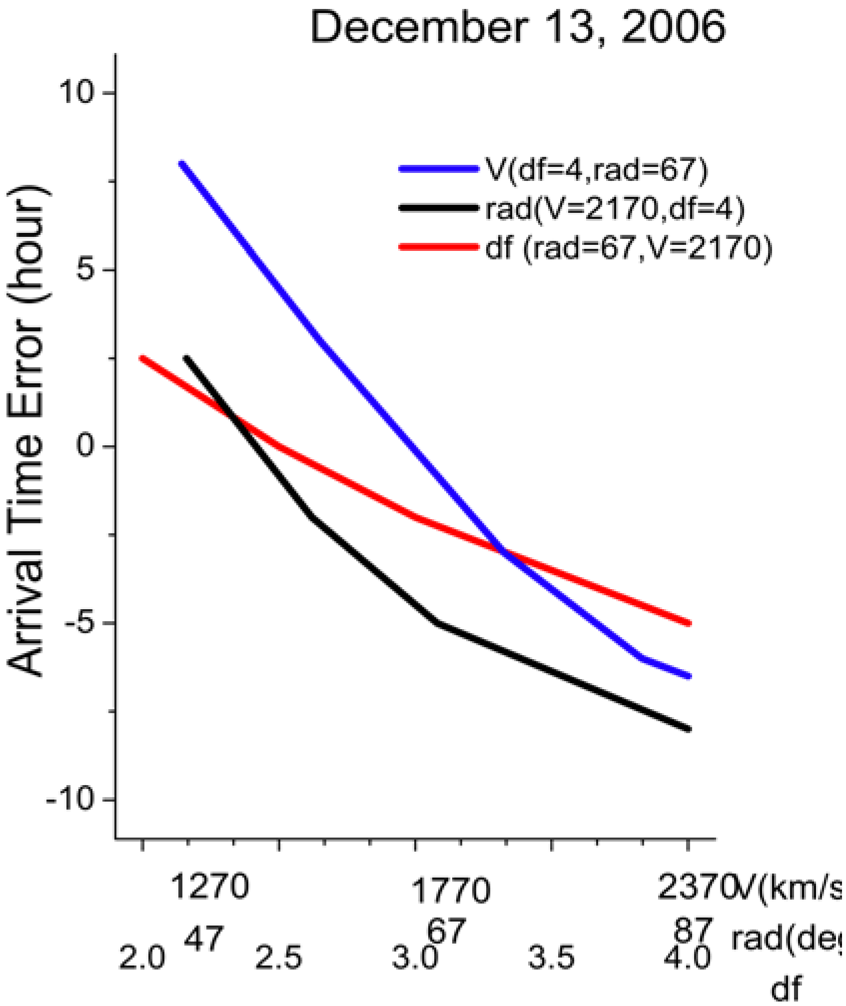
Magnitude of CME Impact on the Magnetosphere

B_*^{max} and $r_{\text{mp}}^{\text{min}}$ 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.
- Taktakishvili et al, 2009, *Space Weather*, **7**, 6.

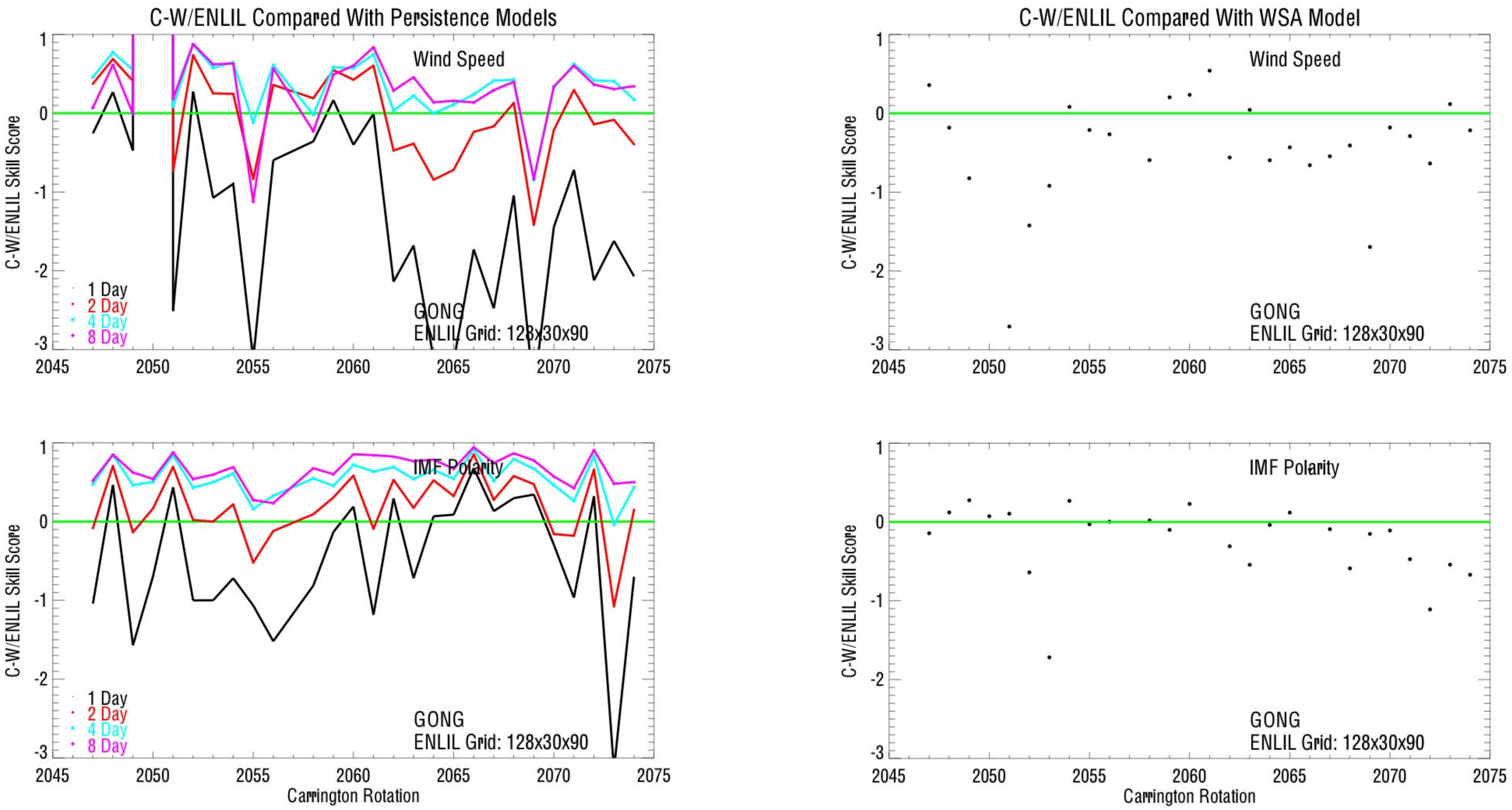
Future Plans

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

CORHEL V4

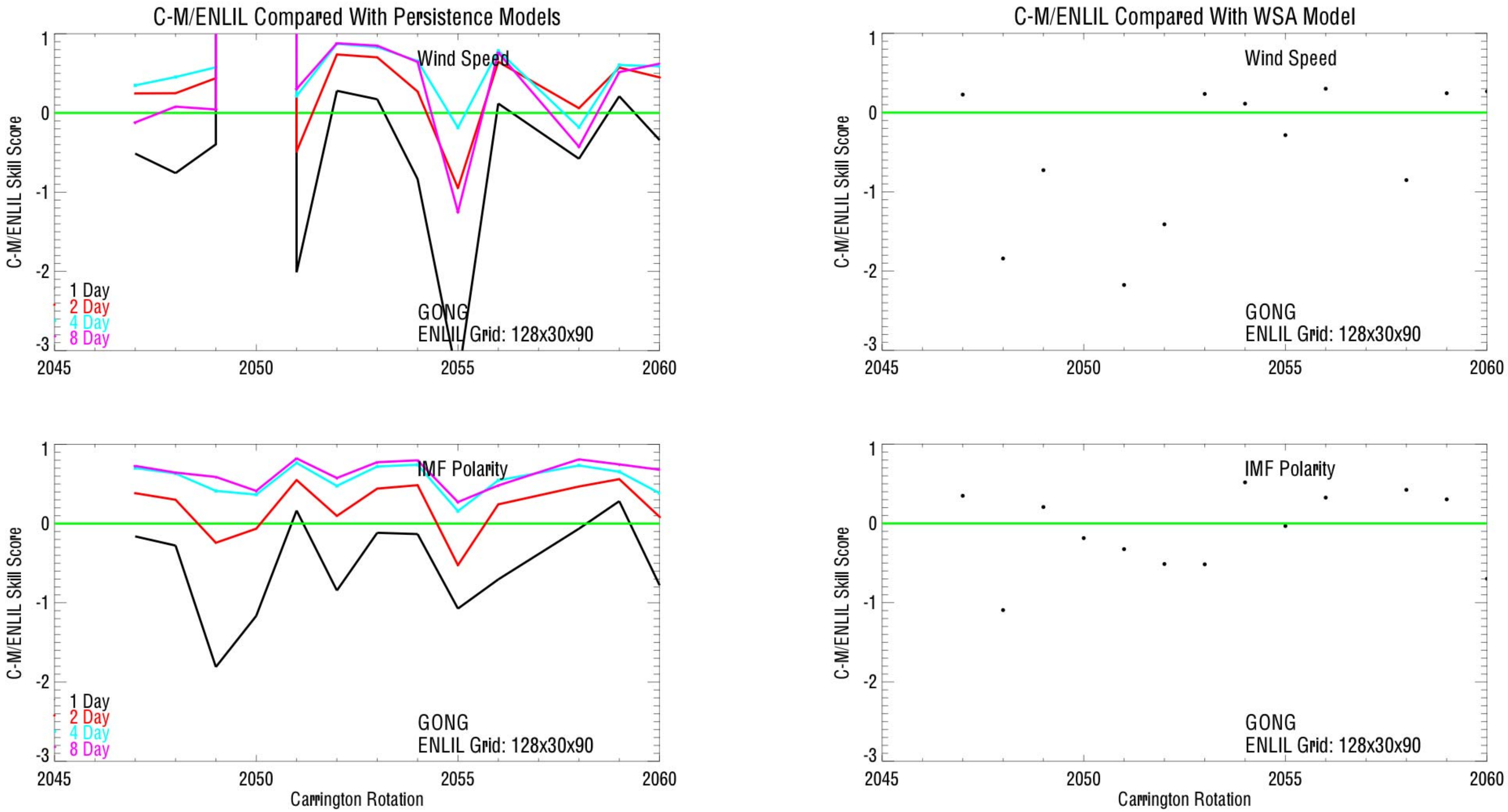
- Plan to test
  - MAS-p/ENLIL
  - MAS-p/MAS-p
  - WSA-C/ENLIL
- Issues
  - What convergence requirements to use for MAS ?

CORHEL V4 – WSA-C/ENLIL



Caveat : Need to do careful double-checking of these results!

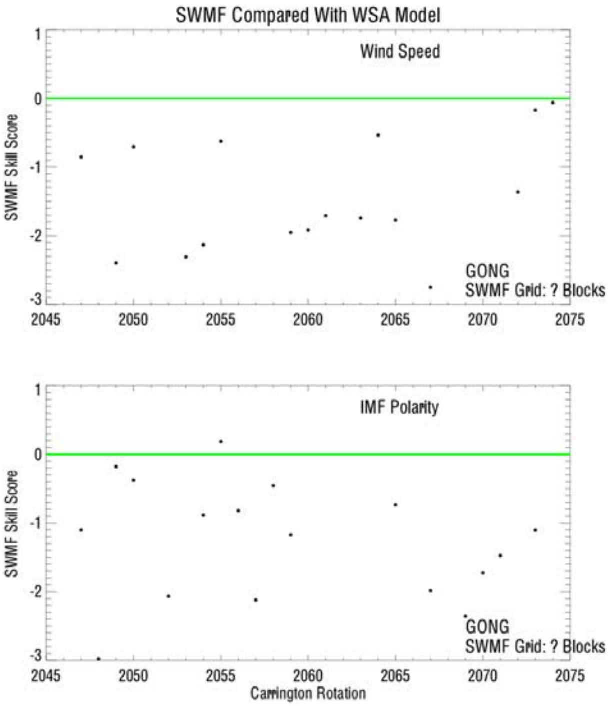
CORHEL V4 – MAS/ENLIL

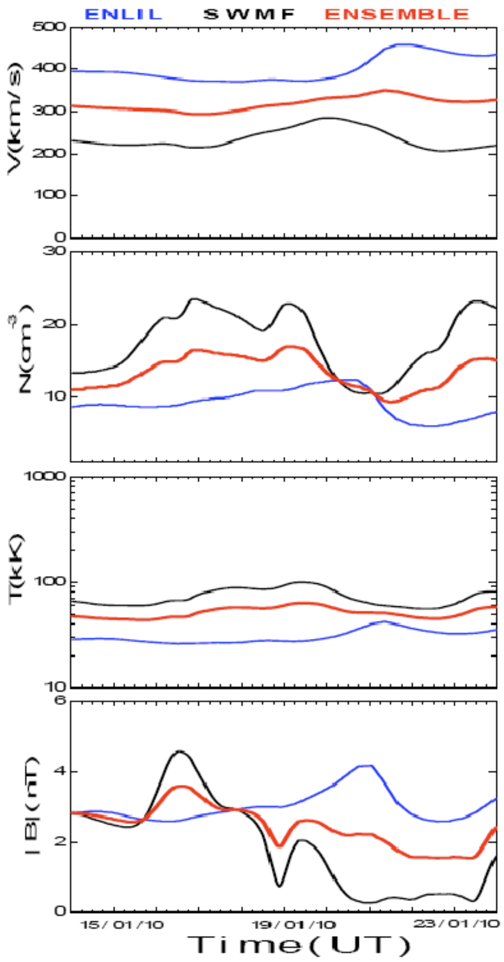


Caveat : Need to do careful double-checking of these results!

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

MacNeice, 2009, *Space Weather*,**7**,6.

Taktakishvili et al, 2009, *Space Weather*, **7**, 6.

MacNeice,P., 2009, *Space Weather*,**7**,12.

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

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