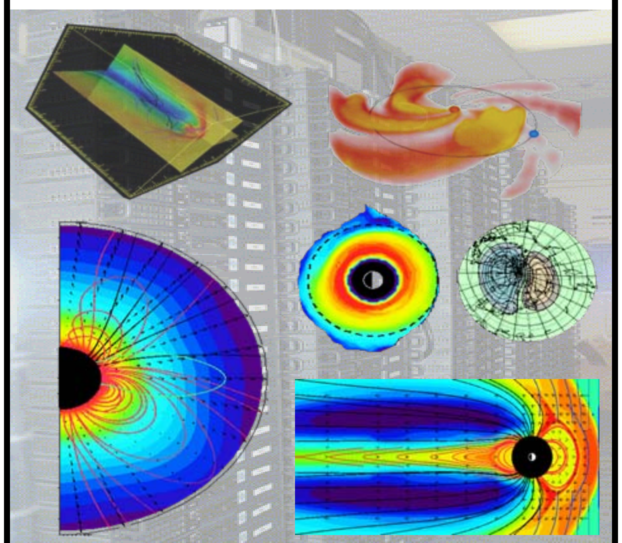
Community Coordinated Modeling Center



Preparing Heliospheric Models for Space Weather Operation – A CCMC Perspective

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Overview

- Validation : How good are the current Solar and Heliospheric models?
  - Ambient
  - Transient – Cone model
- ‘Realtime’ Cone Model Transitioning
- Outlook – new models

Goals of Validation

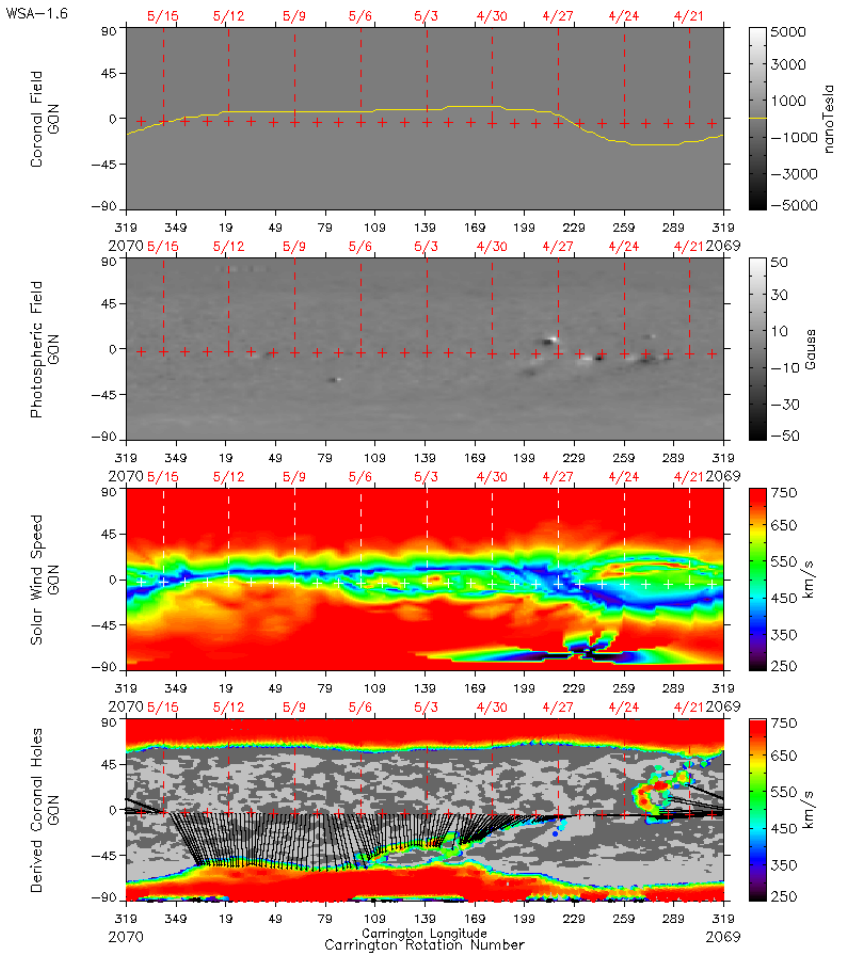
- Establish an ongoing, independent, and consistent validation program applicable to the general class of models
  - Semi-automated for efficiency when applied to new or upgraded models
- Determine which models give best forecasts for observables of interest?
- Quantify their prediction performance
-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

Solar/Helio Models at CCMC

- PFSS
- WSA
- WSA/ENLIL
- 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.

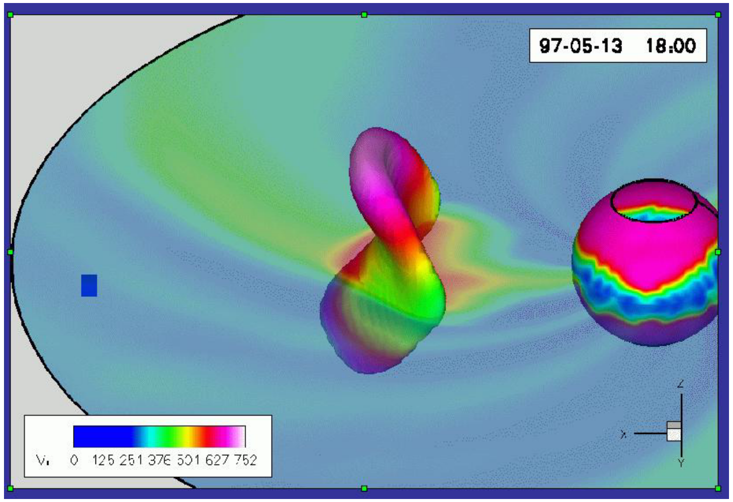
Wang-Sheeley-Arge Model (Arge)

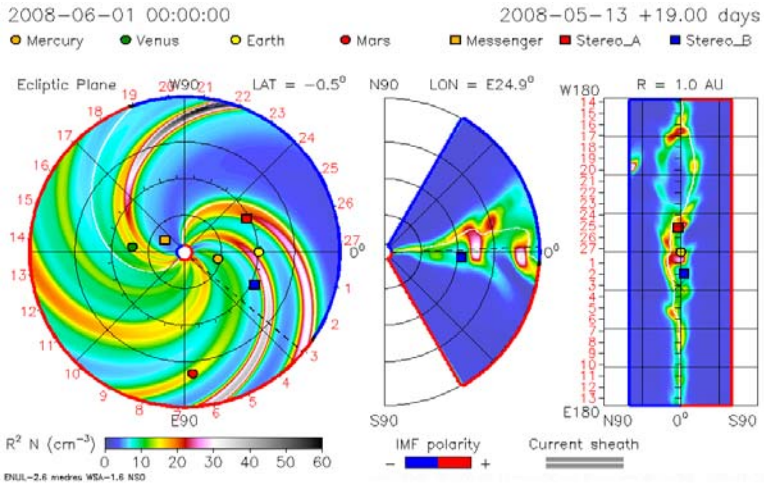
- Time independent, semi-empirical model of corona and heliosphere
- Three Components
  - Source surface to $2.5r_s$
  - Schatten current sheet from 2.5 to $5r_s$
  - Kinematic solar wind from $5r_s$ to 1AU
- Input: Photospheric synoptic magnetograms
  - Uses 72 harmonics (2.5° resolution)
  - We use 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



WSA/ENLIL (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 $21.5r_s$
  - $v \rightarrow (v - 50)$ 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





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

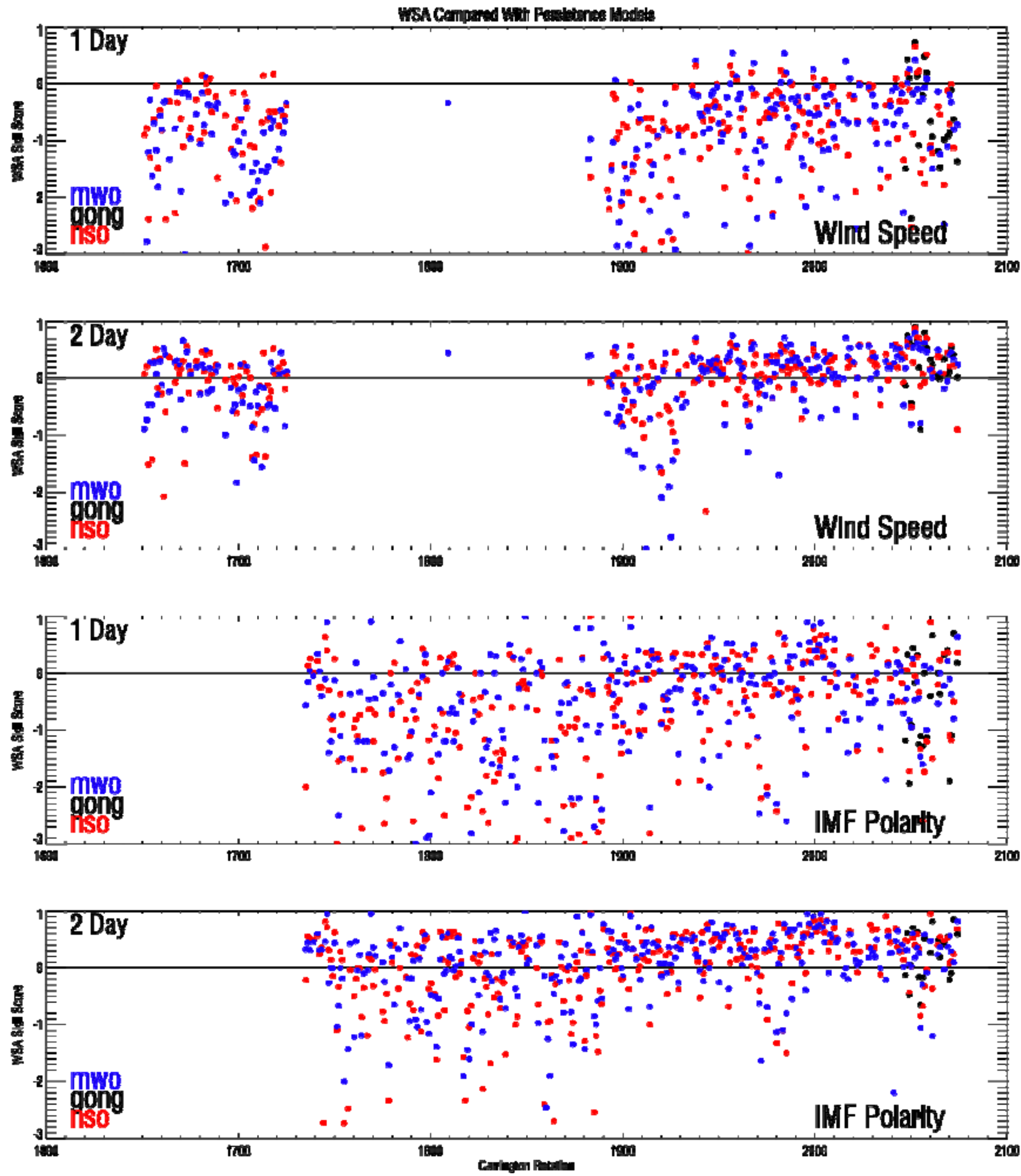
WSA Skill Scores

Standardized definition (Brier, 1950)

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

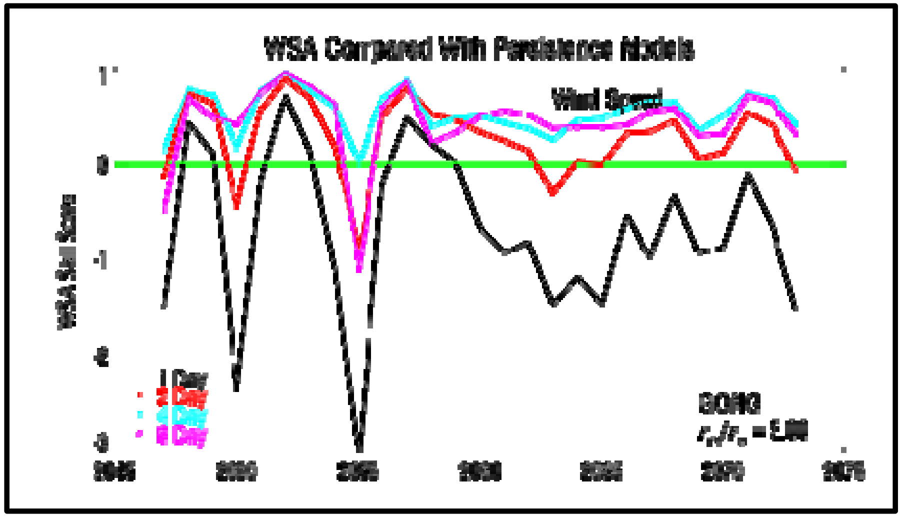
$$M_F^{AB} = 1 - \frac{D_F^A}{D_F^B}.$$

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

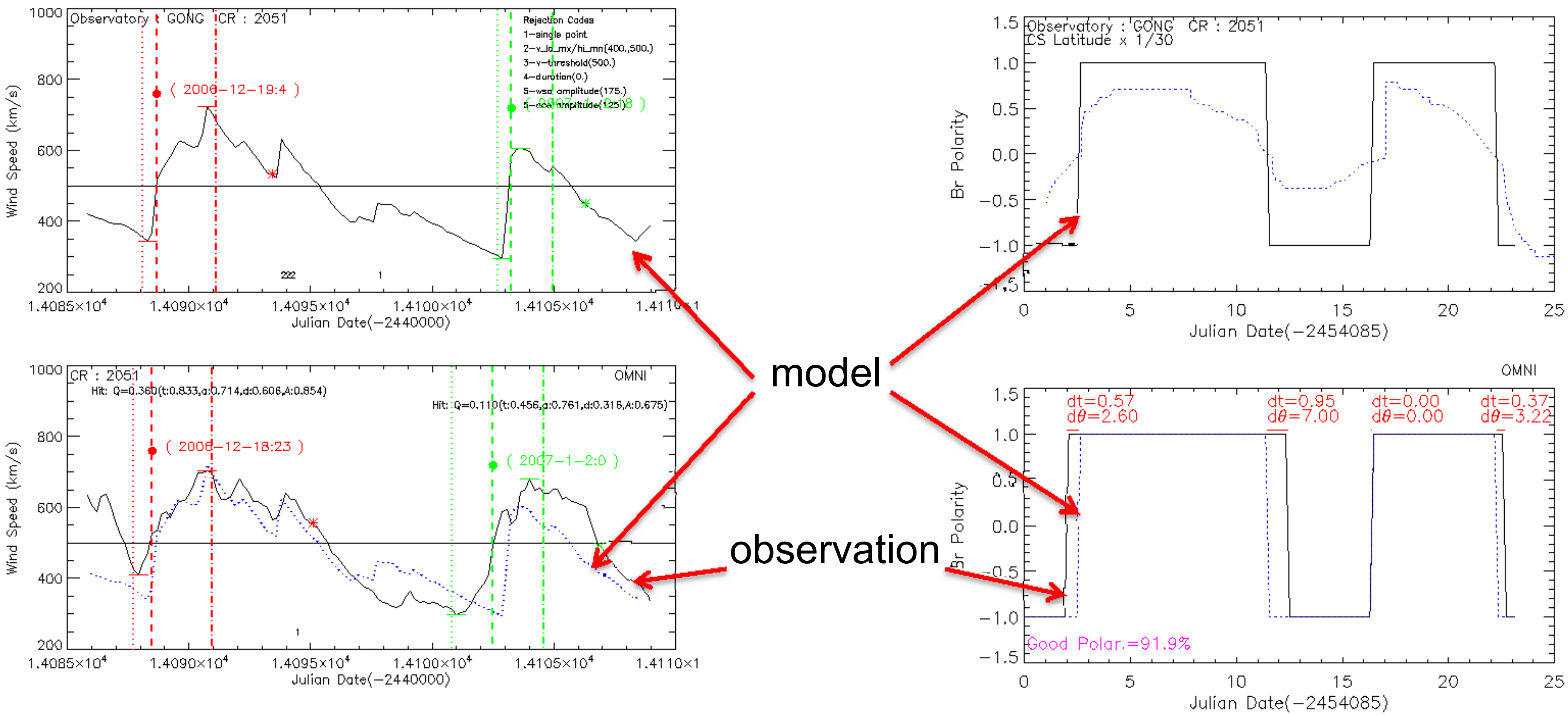
	Velocity		B_r Polarity	
	Quiet	Active	Quiet	Active
Reference Model				
Persistence (1 day)	−1.10	−0.87	−0.96	−0.87
Persistence (2 day)	−0.04	−0.03	−0.07	0.00

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

WSA Event Detection

High Speed Events

IMF B_r Polarity



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

WSA Event Detection

WSA (GONG,NSO,MWO average)

HSE

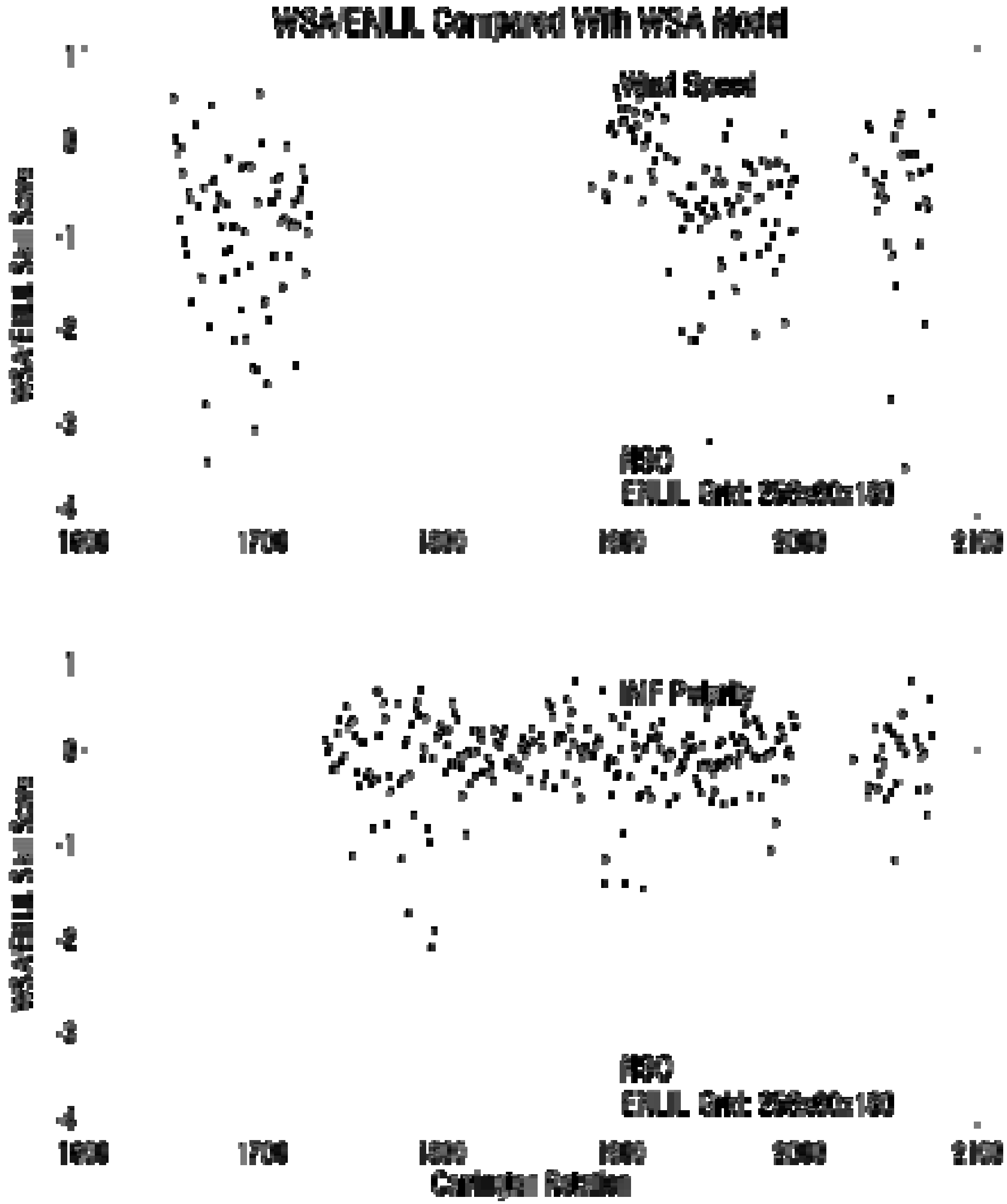
Hit Rate 39%
Miss Rate 61%
False Positive Rate 39%

B_r Polarity

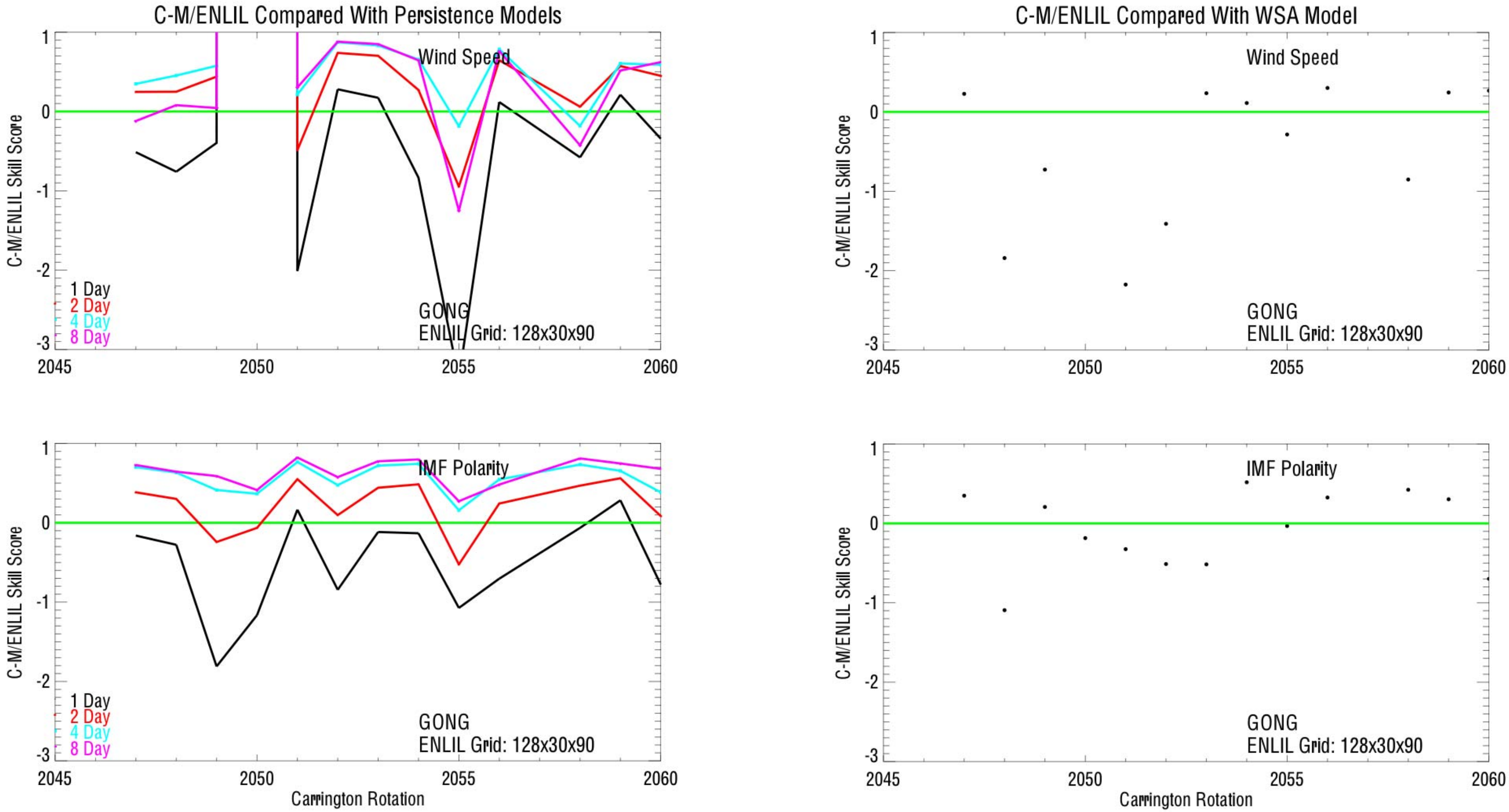
Hit Rate 61%
Miss Rate 39%
False Positive Rate 11%
IMF Polarity correct 76% of time.

WSA/ENLIL Skill Scores

- Full NSO archive
- 256x60x180 – 2^{o} resolution
- Average skill scores
    - Velocity -0.7
    - IMF Polarity -0.15
    - Insensitive to ENLIL grid resolution



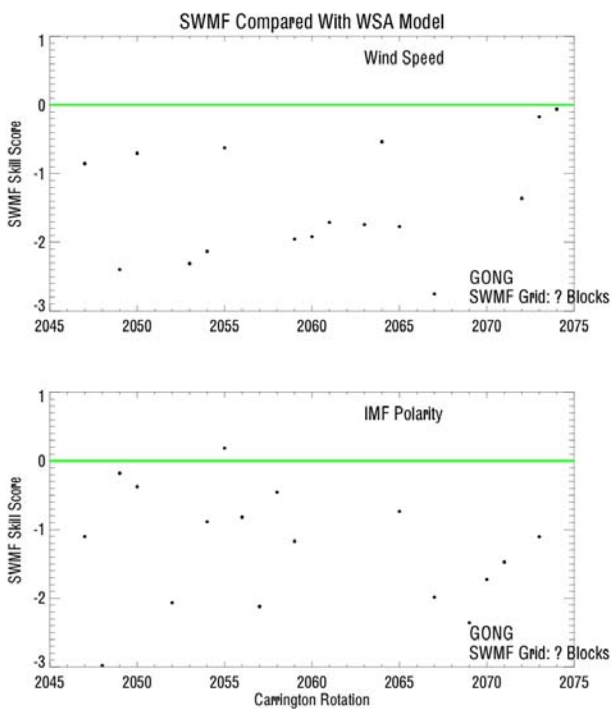
CORHEL V4 – MAS/ENLIL

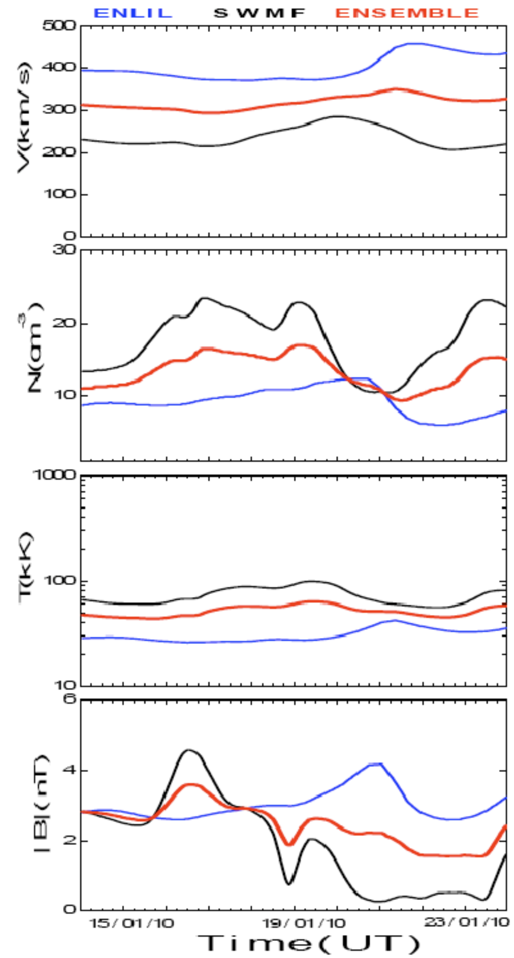


Caveat : Need to do careful double-checking of these results!

SWMF

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





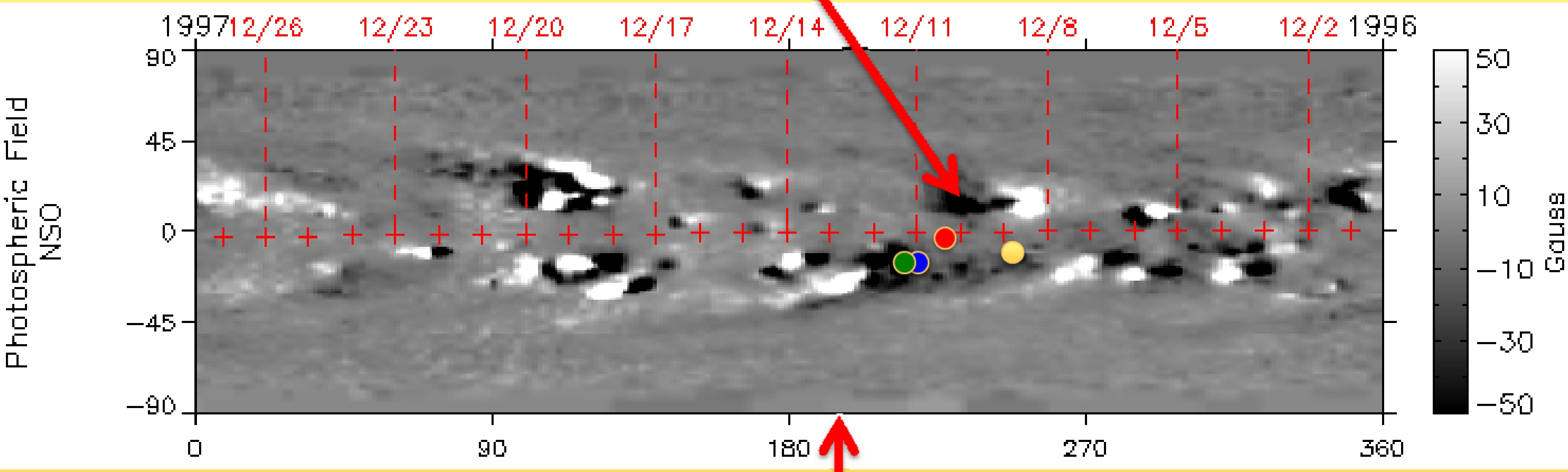
Will be adding WSA shortly

Validating Fieldline Tracing

- Identify impulsive SEP events at 1AU with appropriate ion compositions and clear timing association with a surface event
- Trace from Earth location to surface through model solutions
- Study in progress – Brian Elliott (USAF Acad.)
- Existing event catalogs are 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 15 ‘good’ candidates

Fieldline Tracing

Source Location



- Archimedean Spiral
- PFSS + Spiral
- WSA
- WSA/ENLIL

Sub-earth longitude at time of SEP event

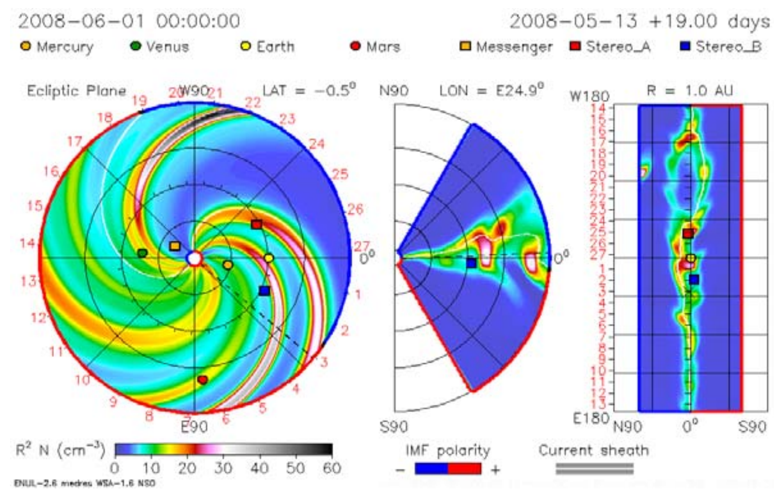
Preliminary indications - simple 'potential corona + spiral IMF' outperforms (?) WSA+Spiral or WSA/ENLIL

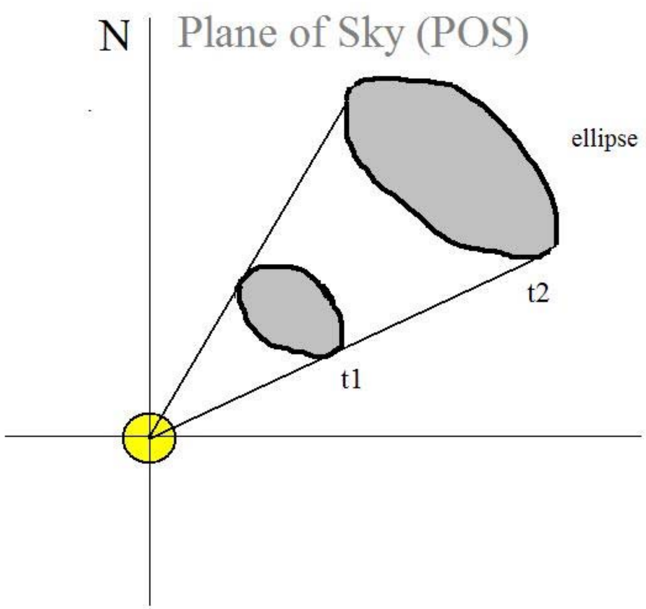
Ambient Wind - Conclusions

- WSA alone is slightly better than 2 day persistence
- WSA/ENLIL marginally worse than 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
- Fieldline tracing – preliminary results suggest simpler potential corona + spiral outperforms(?) more sophisticated models
  - **improvements need better coronal models**

Cone Model Validation (Taktakishvili)

- WSA/ENLIL supports time dependent CME modeling using the simple Cone model approx.
    - transient is a Mass blob injected at ENLIL inner boundary
    - carries no internal magnetic field





Zhao et al, 2002; Xie et al 2004.

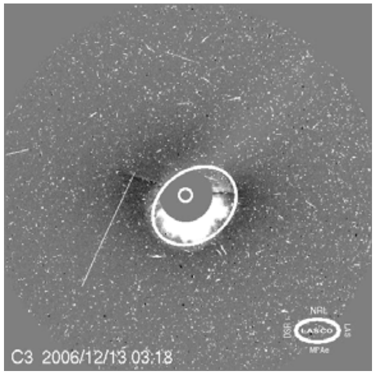
- CME propagates with nearly constant angular width in a radial direction
- The source is near the solar disc center
- CME bulk velocity is radial and the expansion is isotropic

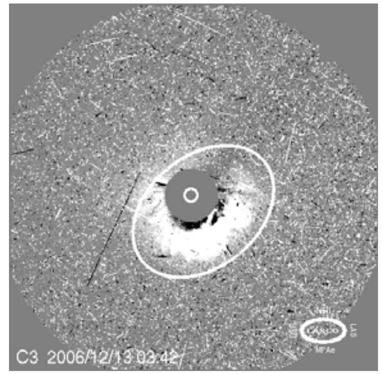
The projection of the cone on the POS is an ellipse

Earth directed CMEs appear as Halos in LASCO images

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

Chose 14 halo CMEs from the catalogue

- clear halo in LASCO/C3 images
- clear shock arrival time observed by ACE
- estimated initial plane of sky velocities > 700 $km.s^{-1}$

Tested

- CME arrival time prediction
- Magnitude of impact on the magnetosphere

Skill Scores relative to 2 reference models

1. Mean speed
   - constant speed v=850km/s – average of all halo CMEs in catalog 1996-2006
2. Gopalswamy et al ESA model
   - empirical, relates CME acceleration to initial observed speed

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

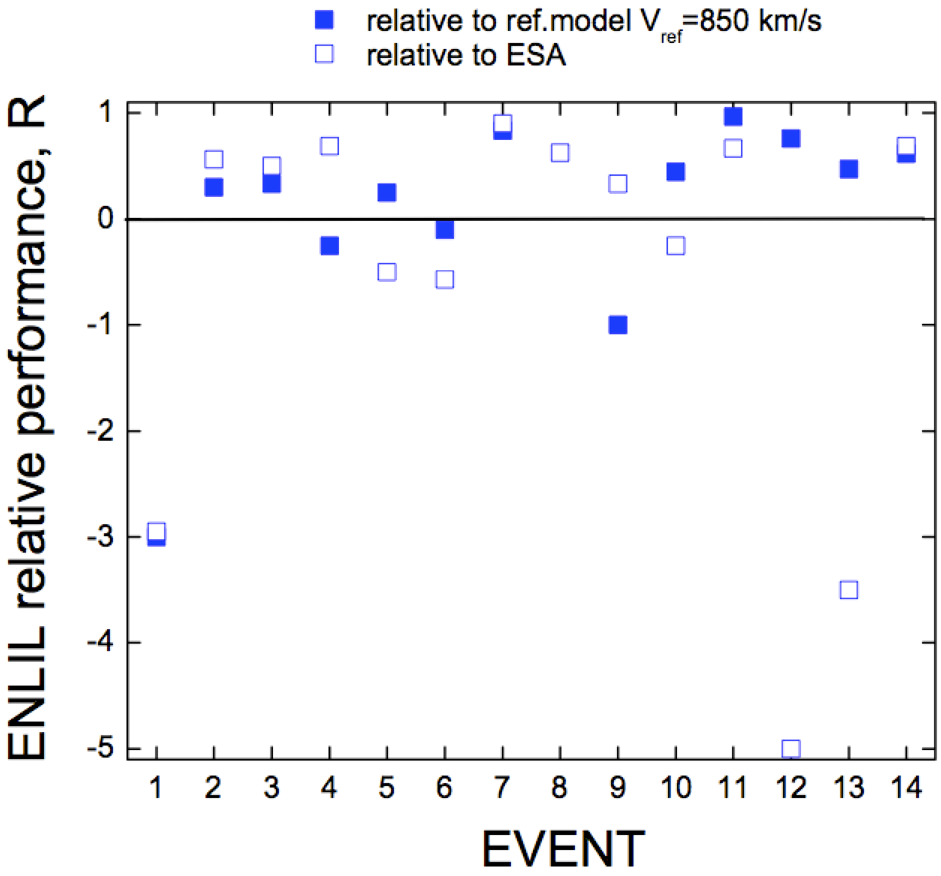
CME Shock Arrival Time Prediction Metrics

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

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

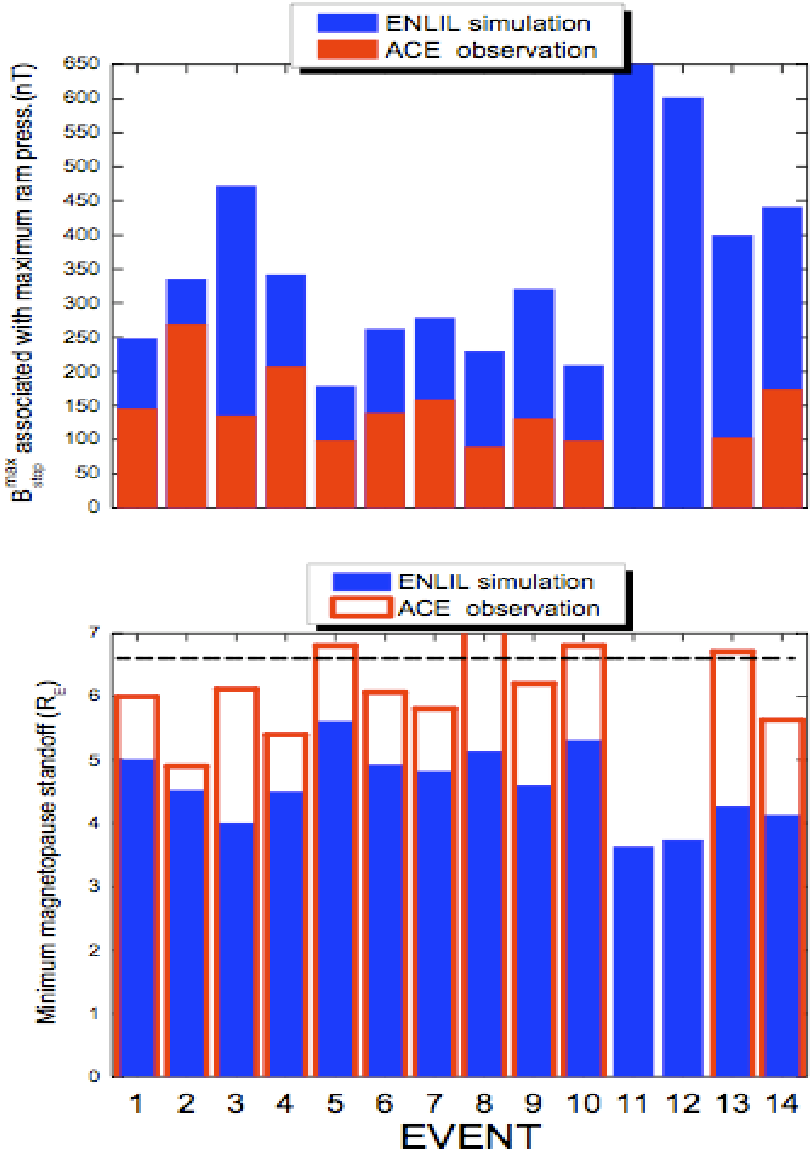
v=850: avg. $|\Delta t_{err}|$: **~ 10.9 h**

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



Ram pressure in the modeled CMEs is to high compared with ACE observations.

WSA/ENLIL overestimates the magnitude of the CME impact on the magnetosphere.

Magnetopause Standoff Distance

Cone Model Validation Summary

- Studied 14 large CME events and comparing model results to the ACE satellite observations;
- The average shock arrival time error is better than the reference models by factors of 1.5 – 2.
- 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.

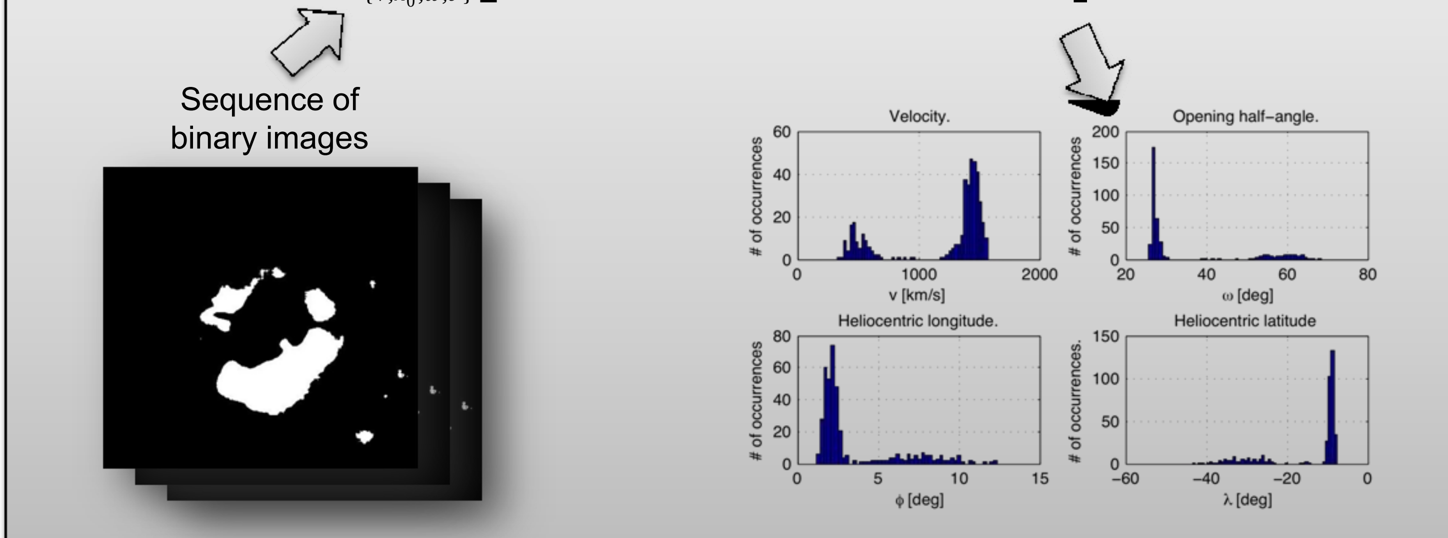
Cone Model Operations and Transitioning

- Testing ‘Realtime’ use of model
  - AFWA monitors LASCO difference image sequences on the CCMC ISWA site 24/7
  - Issues alert when Halo CME is observed
  - When alerted, operators at CCMC derive Cone parameters, run Cone models, issue hit/miss/ arrival time/ magnitude of storm estimates
- Realtime system delivered to SWPC
- Collaborating with SWPC on promoting next generation of Cone-type models.

Cone Model Development (Pulkkinen)

- Automated LASCO analysis in development (Pulkkinen et al 2009, and poster)
    - Statistical analysis of parameter fitting naturally supports ensemble forecasting and confidence

$$\min_{\{v,x_0,\omega,\theta\}} \left[\sum_i \left((y_i - \hat{y}_i)^2 + (z_i - \hat{z}_i)^2 \right) + \mu \left| \omega - \omega_0 \right| \right]$$



Next Generation Models

Ambient **CORONA**/Heliosphere

- Tweaking WSA (1 – 2 years)
  - Temporal interpolation of synoptic magnetograms (ADAPT, Arge)
    - Will also improve the fieldline tracing
  - Higher resolution, lower noise, better calibration of magnetograms
- Major Upgrades (5 – 15 years)
  - Time dependent MHD – driven by SDO vector magnetogram data
  - 3 LWS Strategic Capability models due for delivery within 2-3 years
    - Delivery of infra-structure to research community
    - 3 – 10 year window improving numerics (eg kilogauss sunspot fields) and researching how to formulate lower boundary condition (eg degeneracy in induction eqn solution)
    - Breaking dependence on WSA-like tuning

Next Generation Models

CMEs

- Tweaking (within 1-5 years)
  - Cone model with non-uniform mass distribution
  - Cone model mass with preferred direction
  - Flux rope input at corona/heliosphere interface
- Major Upgrades (5 – 15 years ??)
  - Heliospheric propagation – mirrors ambient model development track
  - Eruptive component much more uncertain!
    - Requires MHD models of CME in low corona, coupled to heliosphere
    - Major milestone to watch for – ‘First modeled eruption driven by sequence of observed vector magnetograms and observed surface flows’
      - Until you see this, delivery dates to Ops are just a wild guess!

SEP Forecasting

- Right now we have the Posner statistical model based on early arrival of relativistic e^- which gives about 40 minute warning
- Prompt SEPs forecasting
  - Incremental progress on fieldline connectivity (all clear / not all clear forecasting)
  - For anything quantatitive – don’t hold your breath
- Delayed SEPs – expecting delivery of first shock acceleration models coupled to heliospheric MHD codes this year (eg CISM’s SEPmod)
  - Development phase – still firmly in research world
  - Will need more complete ICME models with internal fields

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*

Pulkkinen,A. et al, *Nov.* 2009, *Solar Phys*.