VALIDATING SOLAR WIND PREDICTION USING THE CURRENT SHEET SOURCE SURFACE MODEL

Bala Poduval

Research Affiliate, Space Science Institute, Boulder, CO

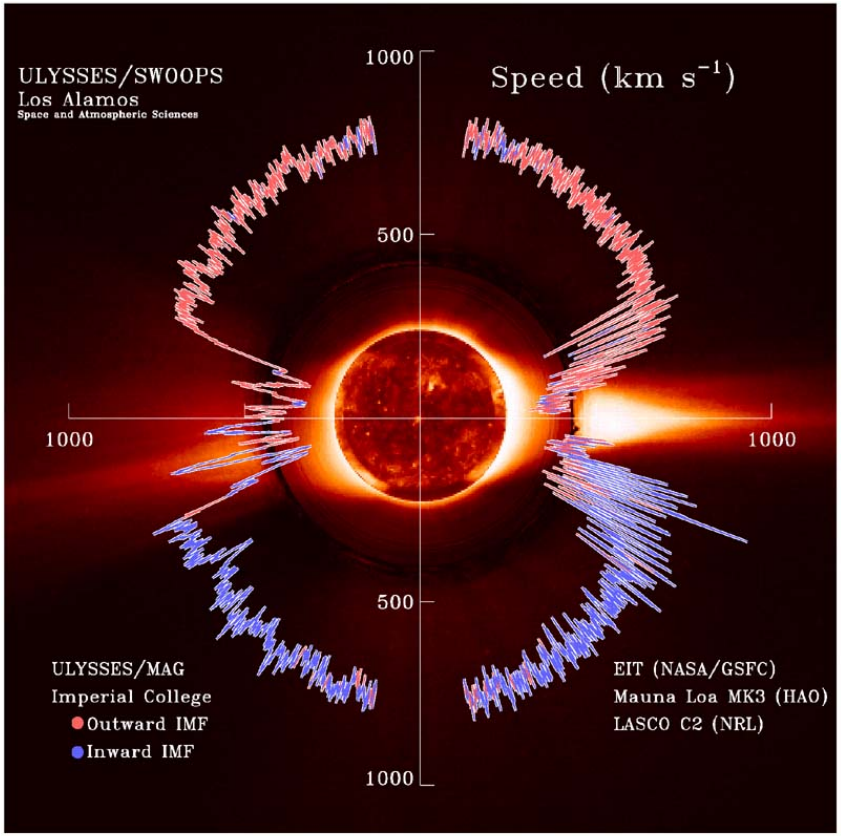
BIMODAL SOLAR WIND

Biermann 1951 —> Parker 1958 —> MARINER (Neugebauer & Snyden 1966)

Subsequent missions —> dual nature of solar wind (slow & fast)

Recent studies —> steady & unsteady based on ionic composition & charge states e.g. Zurbuchen et al., 1999, 2002 Antiochos et al., 2011, ApJ, 731

BIMODAL SOLAR WIND



SLOW SOLAR WIND

origin of fast wind, large-scale structure of solar wind & heliospheric magnetic field – reasonably well-understood
origin of slow solar wind: still controversial

influence of solar/coronal magnetic field
direct measurements of coronal magnetic field?
Rachmeler et al. 2013, Bak-Steslicka et al. 2011
Dove et al. 2011 – CoMP

FIELD EXTRAPOLATION MODELS

SOLAR WIND - ORIGIN

Fast wind – coronal holes – open magnetic field

Slow – near streamers – closed magnetic field

Wang & Sheeley, 1990s

All solar winds originate from coronal holes (CH)

fast wind – center
slow wind – near the boundaries

SOLAR WIND - ORIGIN

solar wind speed α 1/fte

$$fte = \left(\frac{R_{phot}}{R_{ss}}\right)^2 \frac{B_{r(phot)}}{B_{r(ss)}}$$

fte – flux tube expansion factor – between photosphere and source surface;

R_{phot}; R_{ss} – radii of photosphere & source surface

$B_{r(phot)}$; $B_{r(ss)}$ – magnetic field

WANG-SHEELEY-ARGE MODEL

Arge and Pizzo, JGR, 105, 2000

Potential Field Source Surface (PFSS) model

$v = 265.0 + (1.5/(1+f_s)^{1/2.5}) * (5.8 - 4.0 * \exp(-\vartheta_b/2.5)^2))^{3.5}$

McGregor et al., JGR, 113, 2008

f_s - flux expansion factor

ϑ_b - the angular distance of the magnetic field foot point from the nearest CH boundary

WSA/ENLIL

NOAA - Space Weather Prediction Center

state-of-the-art space weather prediction model

WSA - ambient solar wind at inner boundary of ENLIL

1-4 day advance warnings of geomagnetic storms cause: earth-directed CMEs and quasi-recurrent solar wind structures - error: 1-2 days

Major single source - background solar wind - WSA due to intrinsic flaws in PFSS model

Current efforts: reduce error to 6-8 hours & improve inner boundary conditions of ENLIL

PFSS MODEL

- Coronal models
- Schatten et al., 1969; Altschuler & Newkirk, 1969
- corona – current free between photosphere & source surface – 2.5 R_{sun} : Hoeksema, 1984
- coronal magnetic field computed from scalar potential obeying LaPlace's law

popular – addresses a variety of problems

e.g. Schrijver & DeRosa, 2003; Luhmann et al., 2009

PURPOSE of ALTERNATE MODEL

corona - not current-free

large-scale plasma structures above 1.5 R_{sun}

➔interaction between magnetic field and electric currents

potential field - over simplification

limitations PFSS —> uncertainties in foot point locations of SW source regions – few tens of degrees in longitude

Poduval & Zhao, JGR 109, 2004

(more quantitative comparison currently underway)

CSSS model - Many advantages over PFSS
better alternate for SW prediction?

PURPOSE of ALTERNATE MODEL

Parker 1958 – solar wind model

above a **reference height** radially directed SW totally controls the magnetic field

to quantitatively model **background** HMF from the observed photospheric field – determine the **reference height & compute coronal magnetic field**

– same for solar wind speed

CSSS MODEL

Solution to magnetostatic equilibrium – electric currents flowing perpendicular to gravity ($1/r^2$) everywhere – expanded as spherical harmonics

Bogdan & Low, 1986; Neukirch, 1995

Zhao & Hoeksema 1995 developed CSSS model

Includes - effects of volume & sheet currents

- source surface

CSSS MODEL

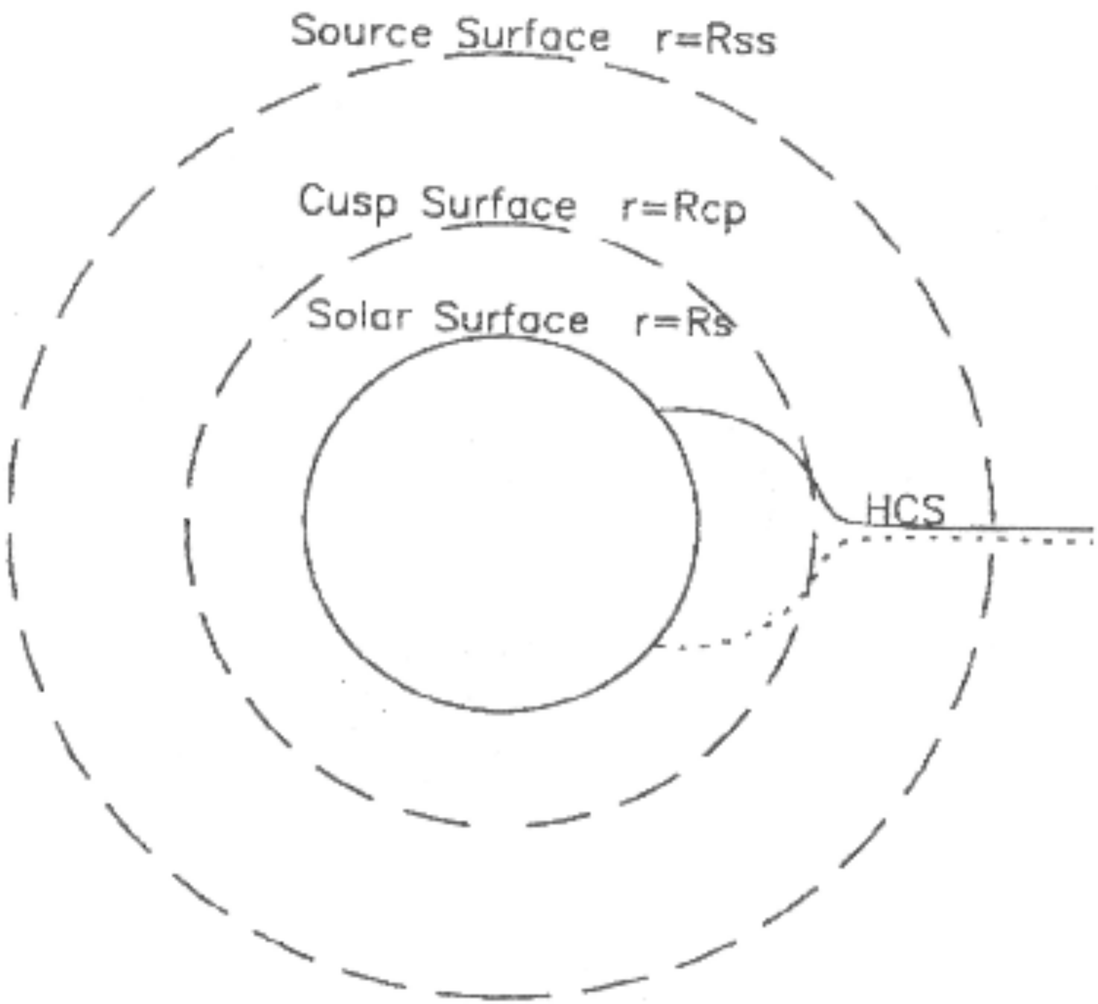
$$J = \frac{1}{\mu_0 r}[1 - \eta(r)]\left[\frac{1}{sin(\theta)}\frac{\partial^2 \phi}{\partial \phi \partial r}\hat{\phi} - \frac{\partial^2 \phi}{\partial \theta \partial r}\hat{\phi}\right] \quad (1)$$

and

$$B = -\eta(r)\frac{\partial \phi}{\partial r}\hat{r} - \frac{1}{r}\frac{\partial \phi}{\partial \theta}\hat{\theta} - \frac{1}{sin(\theta)}\frac{\partial \phi}{\partial \phi}\hat{\phi} \quad (2)$$

where, μ_0 is the magnetic permeability, $\eta(r) = 1 + (a/r)^2$ and $\phi(r, \theta, \phi)$ is a scalar function determined by the boundary conditions at the photosphere and corona (Zhao and Hoeksema, 1995).

GEOMETRY OF CSSS MODEL



COMPARISON

PFSS

- Source surface – 2.5 Rsun
- Magnetic field at SS - open & constrained to be radial
- Latitudinally structured
- Predicts polarity

  Strength - in terms of total unsigned flux crossing the SS

CSSS

- Free to vary – 14 - 15 Rsun
- Open at cusp surface 2.5Rsun

  but not radial until SS
- Coronal magnetic field – uniform - no latitudinal (or longitudinal) dependence – consistent with observations – Smith & Balogh 1995, 2003; Acuña, 2008
- Can predict HMF strength & polarity

DATA

OMNI data – http://omniweb.gsfc.nasa.gov/

Daily averaged solar wind data 1996-1998

minimum, early ascending - solar cycle 23

Photospheric synoptic maps

WSO - 5° lat-long

NSO/Kitt Peak - 1°

METHOD

Step 1: map observed solar wind back to corona

$$\varphi_0 = \varphi_R + \frac{R\Omega}{V_R} \quad \& \quad \vartheta_0 = \vartheta_R$$

ϑ_0, φ_0 – latitude & longitude at source surface

ϑ_R, φ_R – at a distance R from Sun

Ω – angular rotation of the Sun

V_R – the solar wind velocity at R – we used the daily averaged value

METHOD

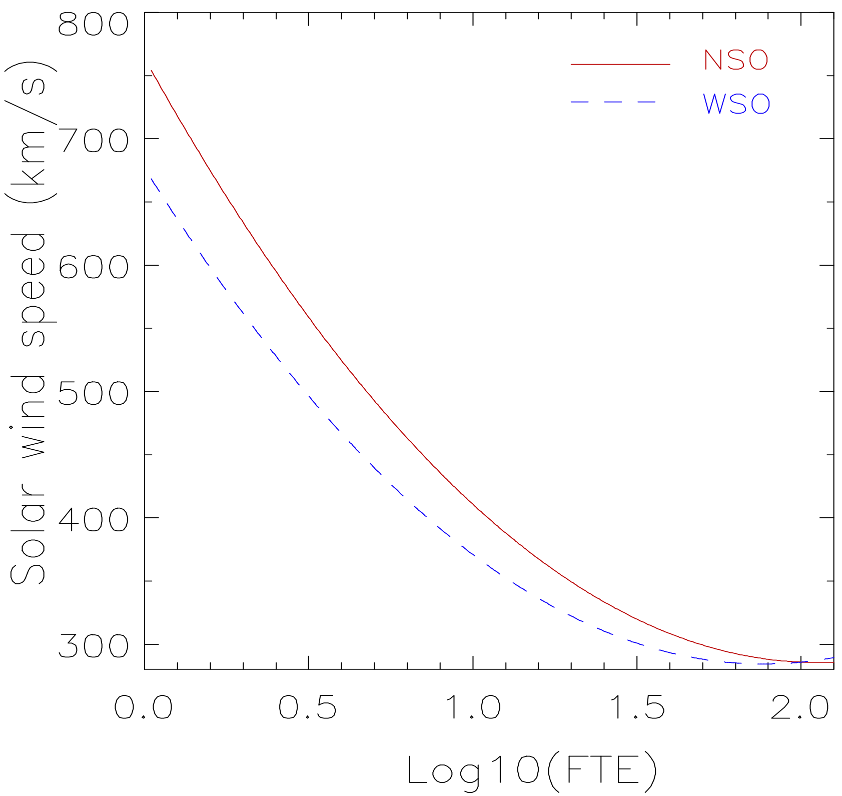
Step 2: map SS locations back to photosphere along open field lines using CSSS & PFSS models

Computed FTE at each solar wind source

predicted solar wind speed - WS relationship

Speed	FTE
> 750	< 4.5
650 – 750	4.5 – 8
550 – 650	8 – 10
450 – 550	10 – 20
< 450	> 20

Quadratic Function



WSO synoptic map

a = 110.3
b = -416.0
c = 676.6

NSO/Kitt Peak synoptic map

a = 113.9
b = 466.6
c = 763.4

RMSE

Evaluate performances of PFSS & CSSS models

Root Mean Square Error – RMSE

Between observed speed and model predictions

$$\text{RMSE ratio} = \frac{\text{RMSE}_{\text{PFSS}}}{RMSE_{CSSS}}$$

SKILL SCORE

$$\text{skill} = 1 - \frac{MSE}{MSE_{ref}} * 100$$

MSE: Mean Square Error

Owens et al., JGR, 110, 2005

METRIC OF ACCURACY

Correlation coefficient – inadequate - good correlation not necessarily imply causality

	CSSS	PFSS	
WSO/NSO	24%	15%	cor coft > 0.5
WSO	1.3		mean RMSE
NSO	1.6		mean RMSE
Mean cor coft	0.23	0.12	NSO
	0.15	0.13	WSO

METRIC OF ACCURACY

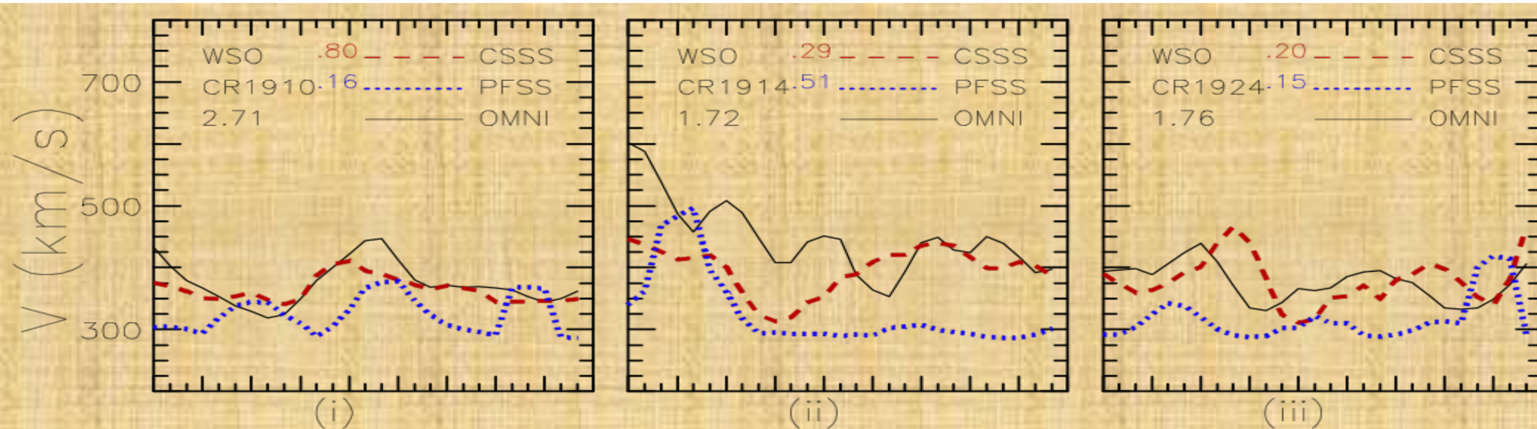
82% with RMSE >= 1.0 => CSSS predictions

Comparable to PFSS predictions

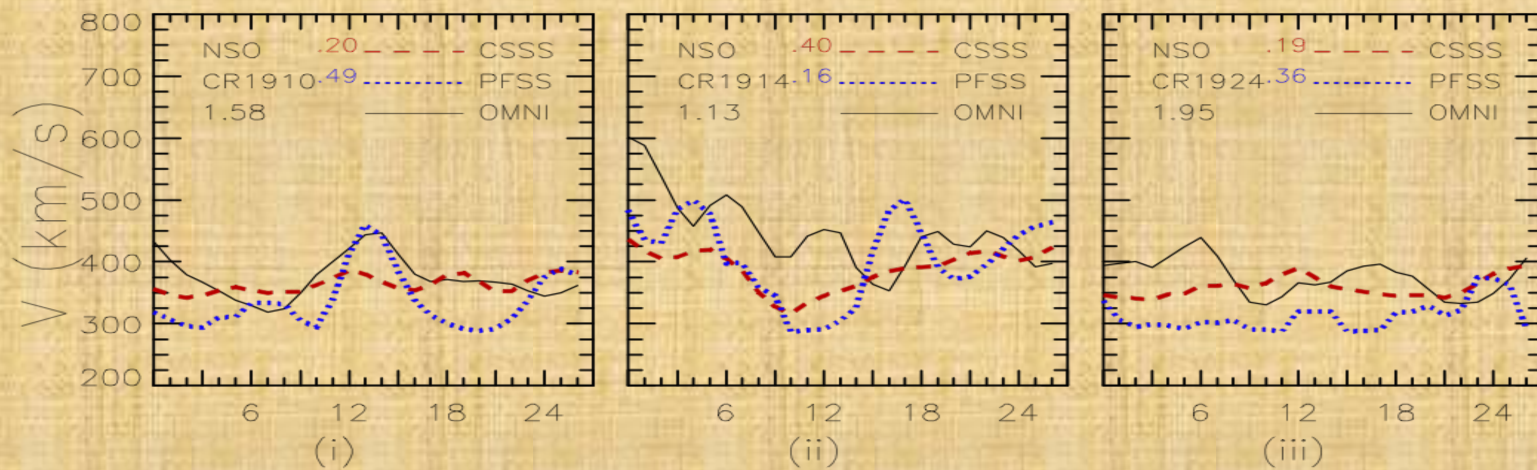
WSO 32% RMSE > 1.3

NSO 55%

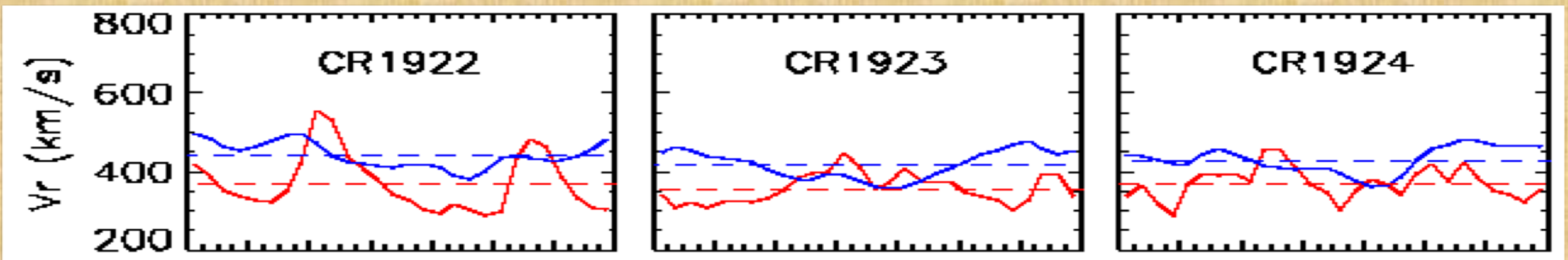
Average RMSE ration between CSSS & WSA/ENLIL – 1.9



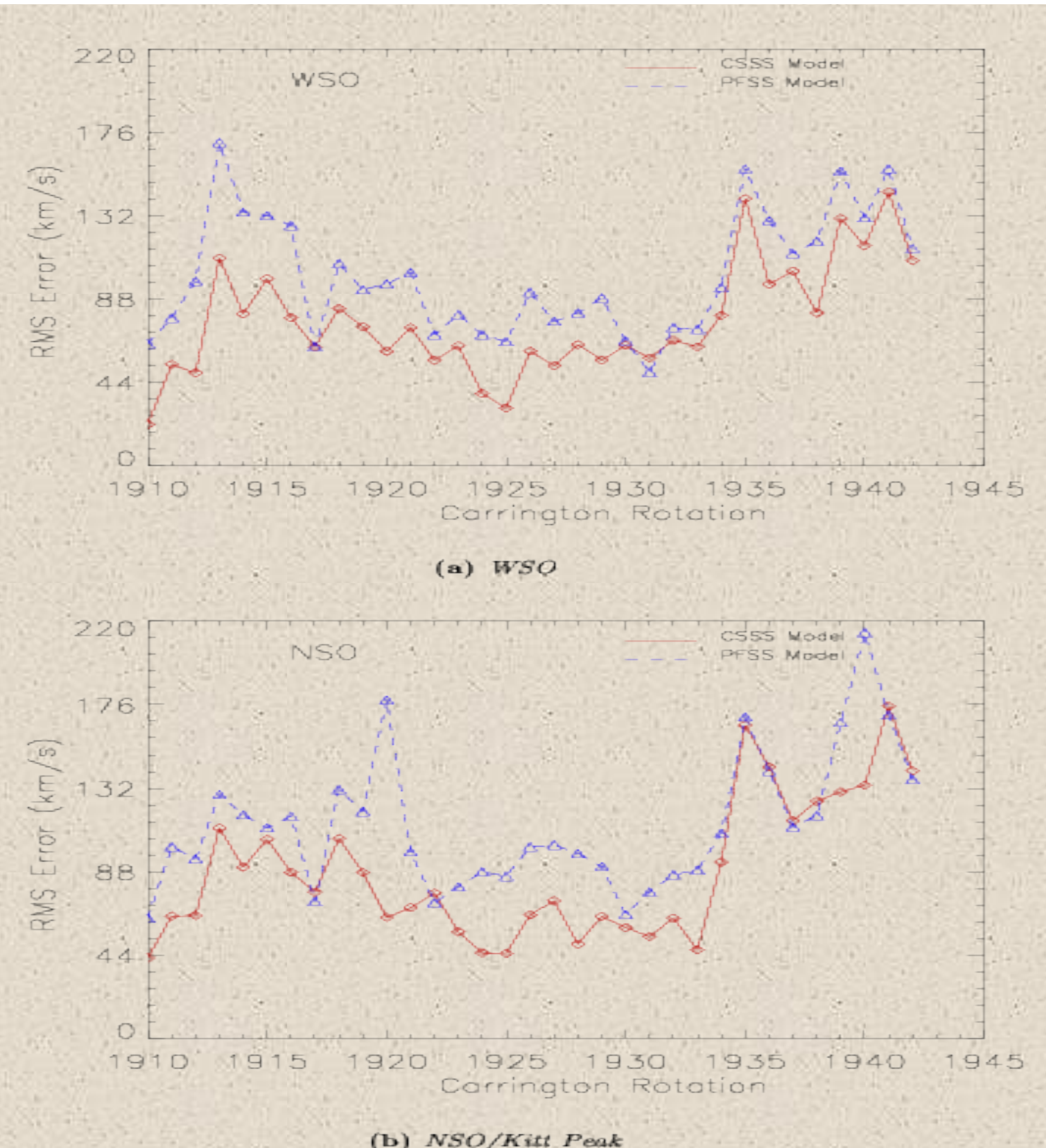
(a) WSO



(b) NSO/Kitt Peak



Time (days)



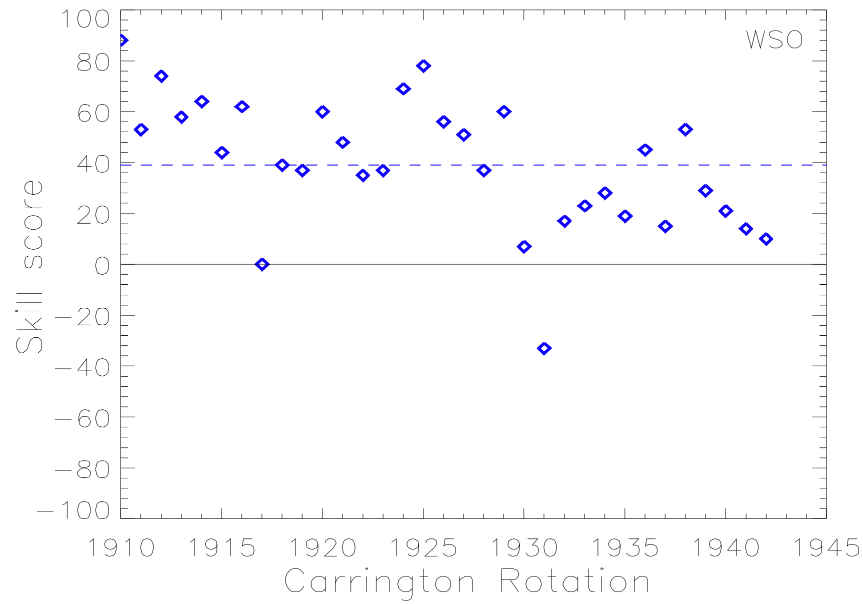
RMSE increases as solar cycle Progresses

Difficulty modelling complex
Global magnetic field

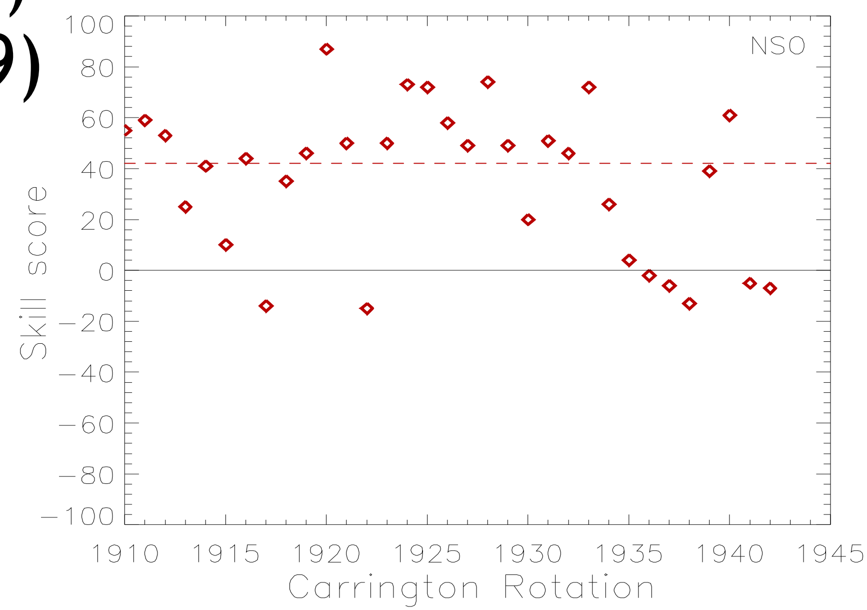
Optimization of free parameters e.g.
R_{cp} = 2.5 Rs_{un}?
Height of cusp varies over wide range
Zhao & Hoeksema 1995;
Cranmer et al., 2007
SS location 15 R_{sun}?

Skill scores comparable

CSSS model: NSO (mean 42) better than WSO (mean 39)



(a) WSO



CONCLUDING REMARKS

For a given synoptic map
CSSS model performs 1.5 – 2 times better than PFSS and WSA/ENLIL

With HMI data, CSSS will predict better

Taking RMS error as metric of accuracy
CSSS model 1.6 time better than PFSS model

CONCLUDING REMARKS

Sun -- Solar wind connectivity:

Mapping observed solar wind back to corona and predicting speed using magnetic field properties at the foot points

represented by FTE

PFSS - solar wind mapped back to 2.5 Rsun

CSSS – 15 Rsun – avoiding the uncertain region below Alfven critical point

CONCLUDING REMARKS

PFSS: magnetic field constrained to be radial 2.5 Rsun
uncertainties in the photospheric foot points — larger

CSSS – magnetic fields allowed to be nonradial
between 2.5 Rsun and 15 Rsun

Better performance of CSSS model — clear indication solar wind sources are traced more accurately — nearly twice than PFSS & WSA/ENLIL

CONCLUDING REMARKS

the source surface location in the CSSS model is free to vary — a great advantage

the coronal and heliospheric magnetic field strengths can be computed — HMF can be compared with the present in situ measurements

forthcoming Solar Orbiter and Solar Probe Plus provide information on coronal conditions within 40 R_{sun} — CSSS prediction can be tested …