SPACE WEATHER AND THE CURRENT SHEET SOURCE SURFACE (CSSS)MODEL

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SPACE WEATHER

conditions in the interplanetary medium causing disruptions to technological systems on Earth and nearby space

FAMOUS SPACE WEATHER EVENTS

December 21, 1806: Alexander von Humboldt observed his compass becoming erratic during a bright auroral event

September 1, 1859: Carrington event, produced solar storm - widespread disruption of telegraph service

November 17, 1882: the Aurora disrupted telegraph service

May 1921: one of the largest geomagnetic storms - caused worldwide disruption of telegraph service and damage to electrical equipments

April 21, 2002: the Nozomi Mars Probe was hit by a large Solar Energetic Particles (SEP) event causing large-scale failure - the mission, already 3 years behind schedule, abandoned in December 2003

FAMOUS SPACE WEATHER EVENTS

August 7, 1972: large SEP event — if astronauts had been in space at the time, it would have been deadly or at least life-threatening — occurred between Apollo 16 and Apollo 17 lunar missions

March 1989: geomagnetic storm — included the full array of space weather effects: SEP, Coronal Mass Ejection, Forbush decrease, ground level enhancement, geomagnetic storm, …

July 14 2000: Bastille Day event occurred near solar maximum of solar cycle 23, producing exceptionally bright aurora

SOLAR WIND

- Parker 1958 — solar wind model
- above a reference height, radially directed solar wind totally controls the magnetic field
- determine this reference height to quantitatively model background heliospheric magnetic field and the solar wind speed

WHY CORONAL MODELS?

- Direct observations of coronal magnetic field — challenging and limited (e. g. Dove et al., ApJ, 731, 2011; Bak-Steslicka et al., ApJL, 770, 2013)
- Models that extrapolate the observed photospheric magnetic field into the corona and beyond

MODELS OF THE CORONA

- Potential Field Source Surface (PFSS) model
- NonLinear Force Free (NLFF) model
- Magnetohydrostatic (MHS) models — Current Sheet Source Surface (CSSS) model
- Magnetohydrodynamic (MHD) models

PFSS MODEL

Schatten et al., 1969; Altschuler & Newkirk, 1969

corona: current free between photosphere and source surface (2.5 Rsun: Hoeksema, 1984; Ph.D. Thesis)

coronal magnetic field - computed from scalar potential obeying LaPlace's law

popular model – addresses a variety of problems

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

SOLAR WIND ORIGIN

Fast wind – coronal holes – open magnetic field

Slow – near streamers – closed magnetic field

Wang & Sheeley, 1990s

All the solar wind 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

WSA: Arge and Pizzo, JGR, 105, 2000

$$v = 265.0 + (1.5/(1+f_s)^{1/2.5}) * (5.8 - 4.0 * \exp(\vartheta_b 2.5)^2))^3$$

(from 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 coronal hole boundary

WSA/ENLIL

ENLIL: state-of-the-art space weather prediction model of NOAA - Space Weather Prediction Center

WSA provides ambient solar wind at the inner boundary of ENLIL

1 - 4 day advance warnings of geomagnetic storms caused by earth-directed CMEs & quasi-recurrent solar wind structures

error: 1-2 days

major single source: WSA background solar wind, due to intrinsic flaws in PFSS model (e.g. Pizzo et al., Space weather, 2012) reduce error & improve inner boundary conditions of ENLIL

NEED OF ALTERNATE MODEL

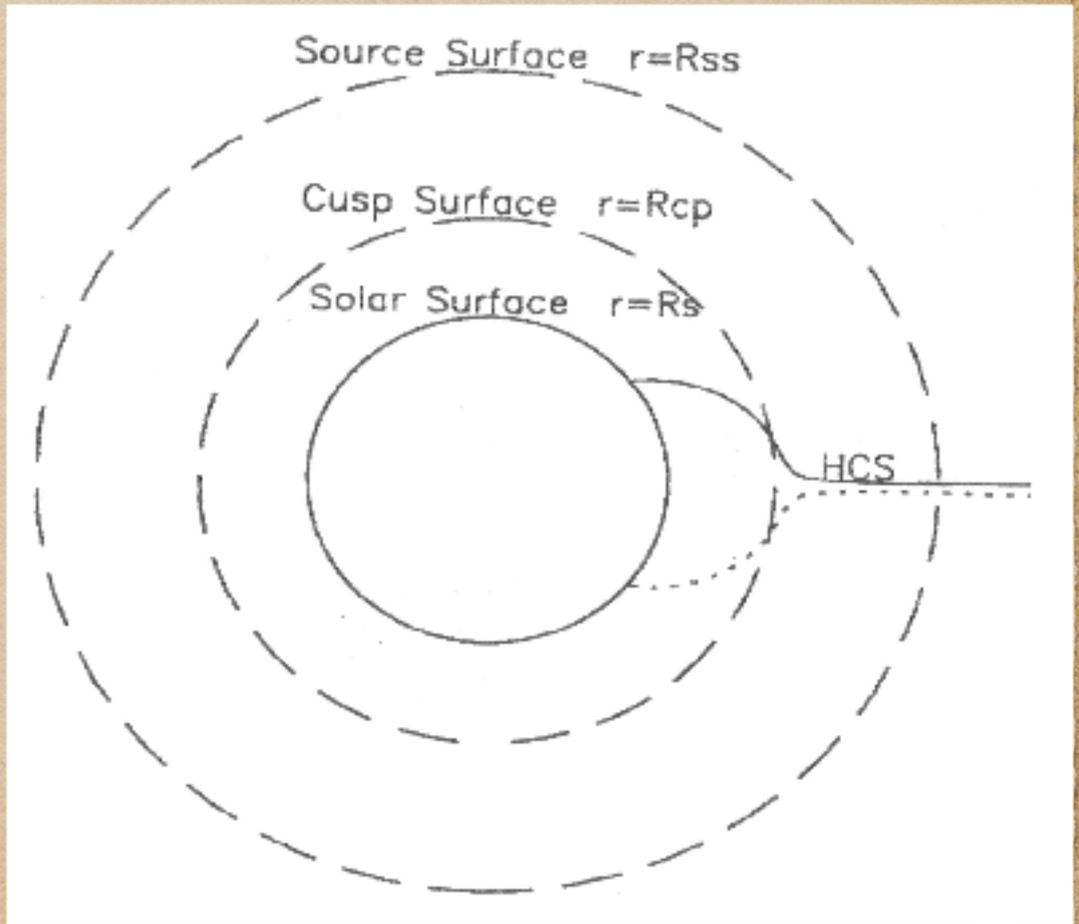
- corona not strictly current free — large-scale plasma structures above 1.5 R_{sun} —> interaction between magnetic field and electric currents
- potential field - over simplification
- PFSS limitations —> uncertainties in the footprint locations of solar wind source regions — a few tens of degrees in longitude (Poduval & Zhao, JGR 109, 2004: more quantitative analysis underway)

GEOMETRY OF CSSS MODEL

BOGDAN & LOW 1986 obtained solution to magnetostatic equilibrium — electric currents flowing perpendicular to gravity ($1/r^2$) everywhere

spherical harmonic expansion

Zhao & Hoeksema 1995 developed CSSS model; includes - effects of volume & sheet currents and 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).

CSSS MODEL

inner region

$$\Phi = \sum_{n=1}^{N_\odot} \sum_{m=0}^{n} R_n^\odot(r) P_n^m(\cos\theta)(g_{nm}^\odot \cos m\phi + h_{nm}^\odot \sin m\phi) \tag{3}$$

$$R_n^\odot(r) = \frac{R_\odot(1+a)^n}{(n+1)(r+a)^{n+1}} \tag{4}$$

middle region

$$\Phi = \sum_{n=0}^{N_c} \sum_{m=0}^{n} R_n^c(r) P_n^m(\cos\theta)(g_{nm}^c \cos m\phi + h_{nm}^c \sin m\phi)$$

outer region

extrapolate computed B out into the heliosphere because

$$B_\theta(R_{ss}, \theta_{ss}, \phi_{ss}) = B_\phi(R_{ss}, \theta_{ss}, \phi_{ss}) = 0$$

COMPARISON OF MODELS

PFSS

- source surface ~ 2.5 R_{sun}
- magnetic field at SS: open & constrained to be radial
- Coronal magnetic field: latitudinally structured
- Predicts polarity, but strength in terms of total unsigned flux crossing SS

CSSS

- Free to vary: 14 - 15 R_{sun}
- Open at cusp surface 2.5 R_{sun} but not radial until SS
- uniform - no lat/lon dependence ~ consistent with observations (Smith & Balogh 1995, 2003; Acuña, 2008)
- Can predict HMF strength & polarity

PRESENT WORK

- we used CSSS/PFSS models to compute FTE
- use the speed-FTE relationship of Wang-Sheeley to predict solar wind speed

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

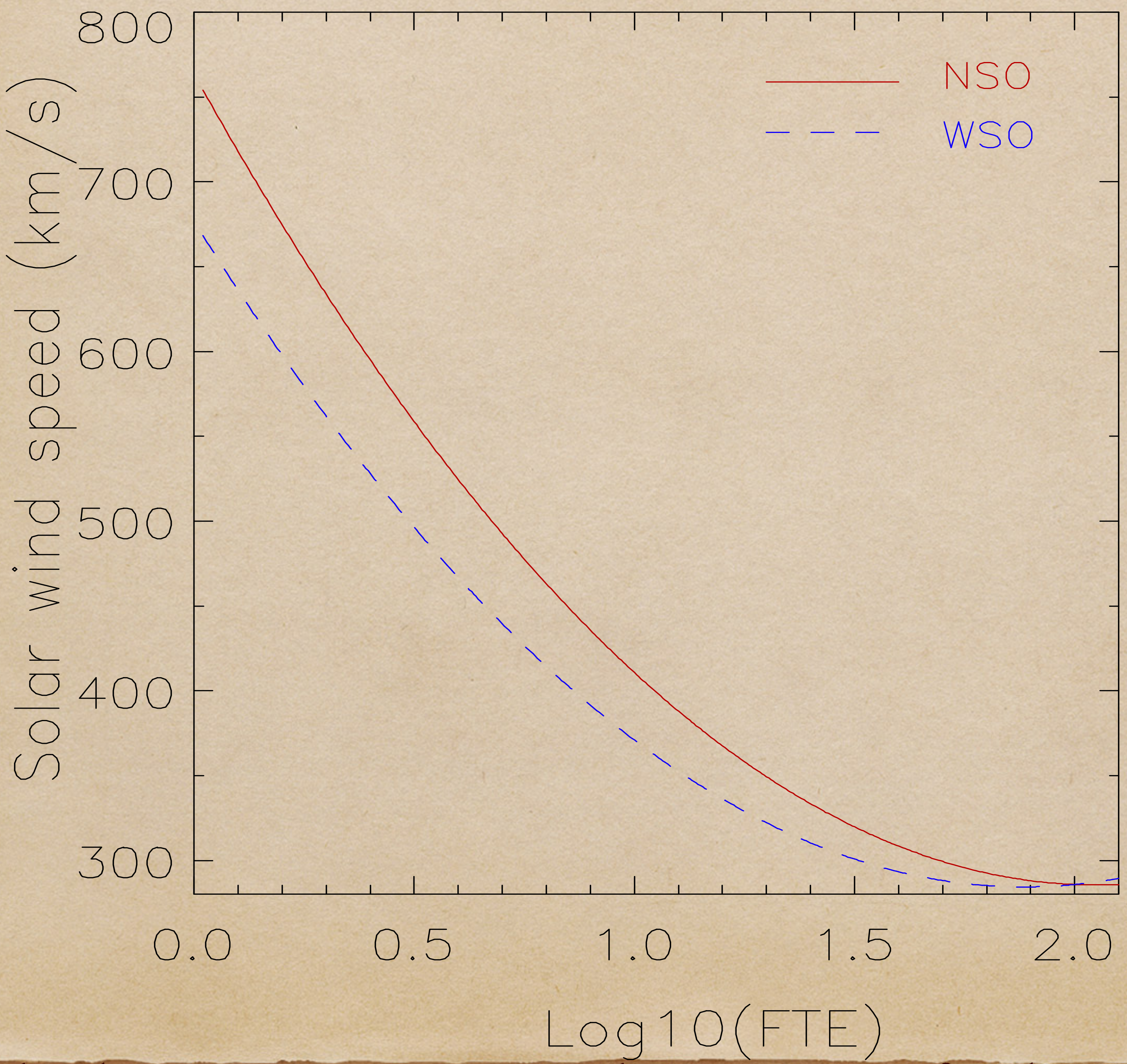
METHOD

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 using 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

a = 110.3

b = -416.0

c = 676.6

NSO/Kitt Peak

a = 113.9

b = 466.6

c = 763.4

SOLAR WIND PREDICTION

- the quadratic function is used for all the subsequent solar wind speed predictions
- used the same functional form for both PFSS and CSSS models

RMSE

Evaluate performances of PFSS and CSSS models

Root Mean Square Error (RMSE) between observed and predicted speeds

$$\text{RMSE ratio} = \text{RMSE}_{PFSS}/\text{RMSE}_{CSSS}$$

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

	synoptic map	CSSS	PFSS
cor coft > 0.5	WSO & NSO	<u>24%</u>	15%
mean cor coft	NSO	<u>0.23</u>	0.12
mean cor coft	WSO	0.15	0.13

METRIC OF ACCURACY

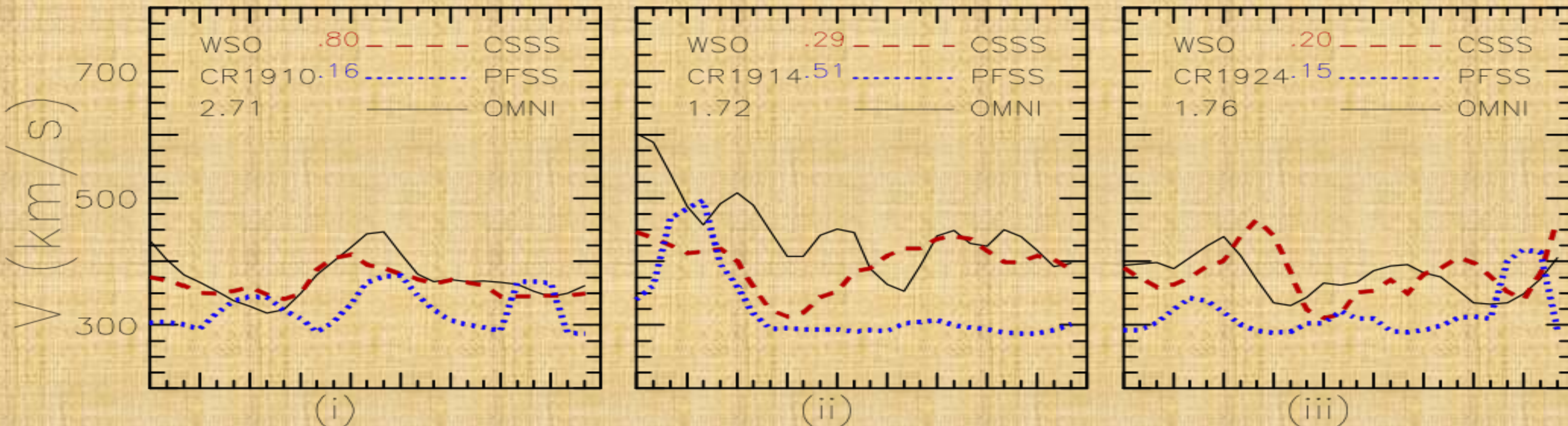
82% with RMSE >= 1.0 →

CSSS predictions are comparable to or better than PFSS predictions

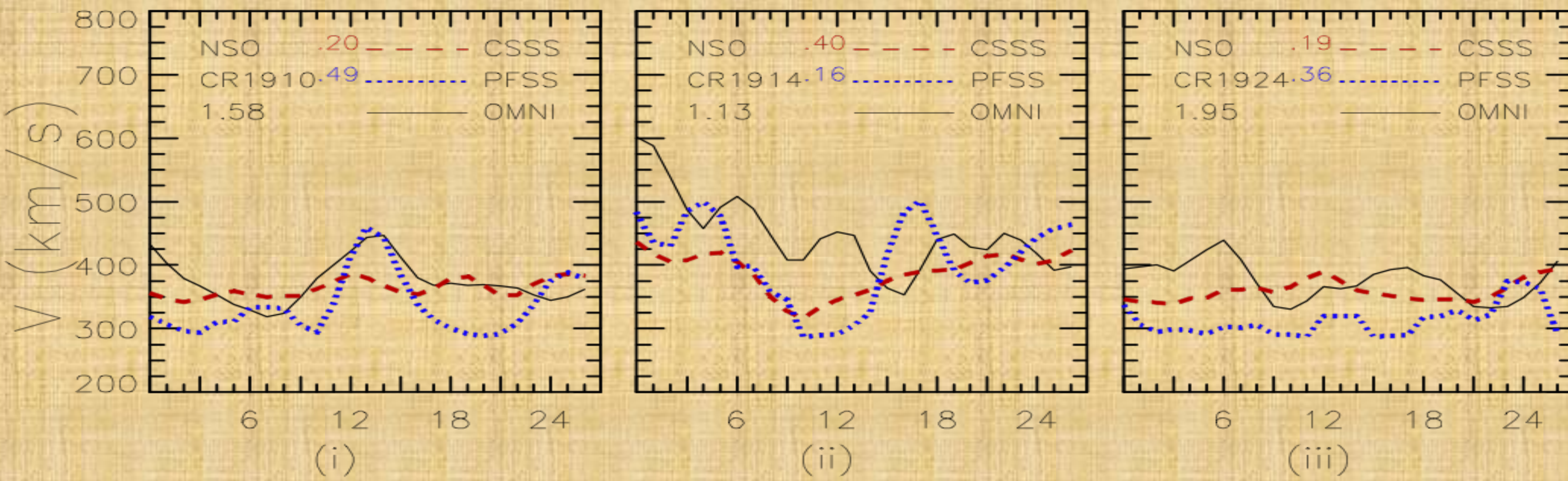
mean RMSE: WSO 1.3; NSO 1.6

RMSE > 1.3: WSO 32%; NSO 55%

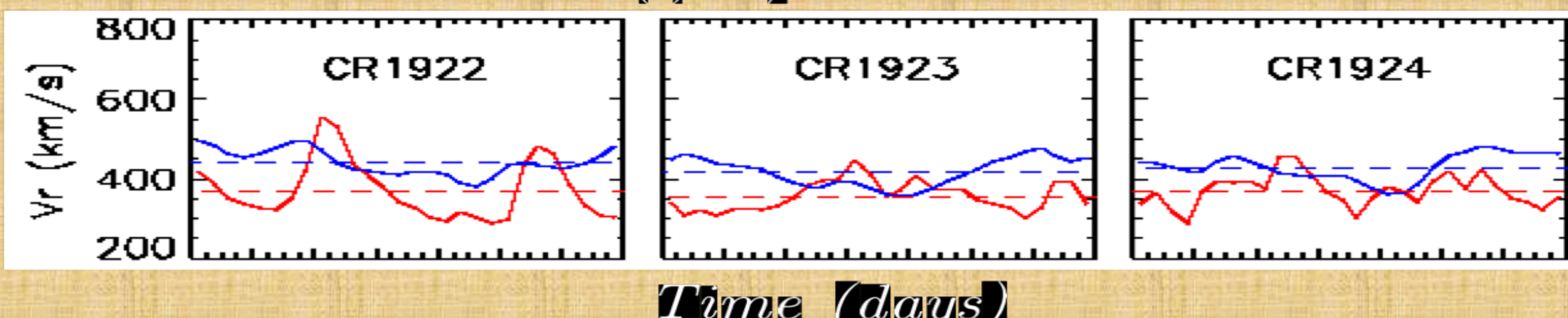
Mean RMSE ratio between CSSS & WSA/ENLIL 1.9



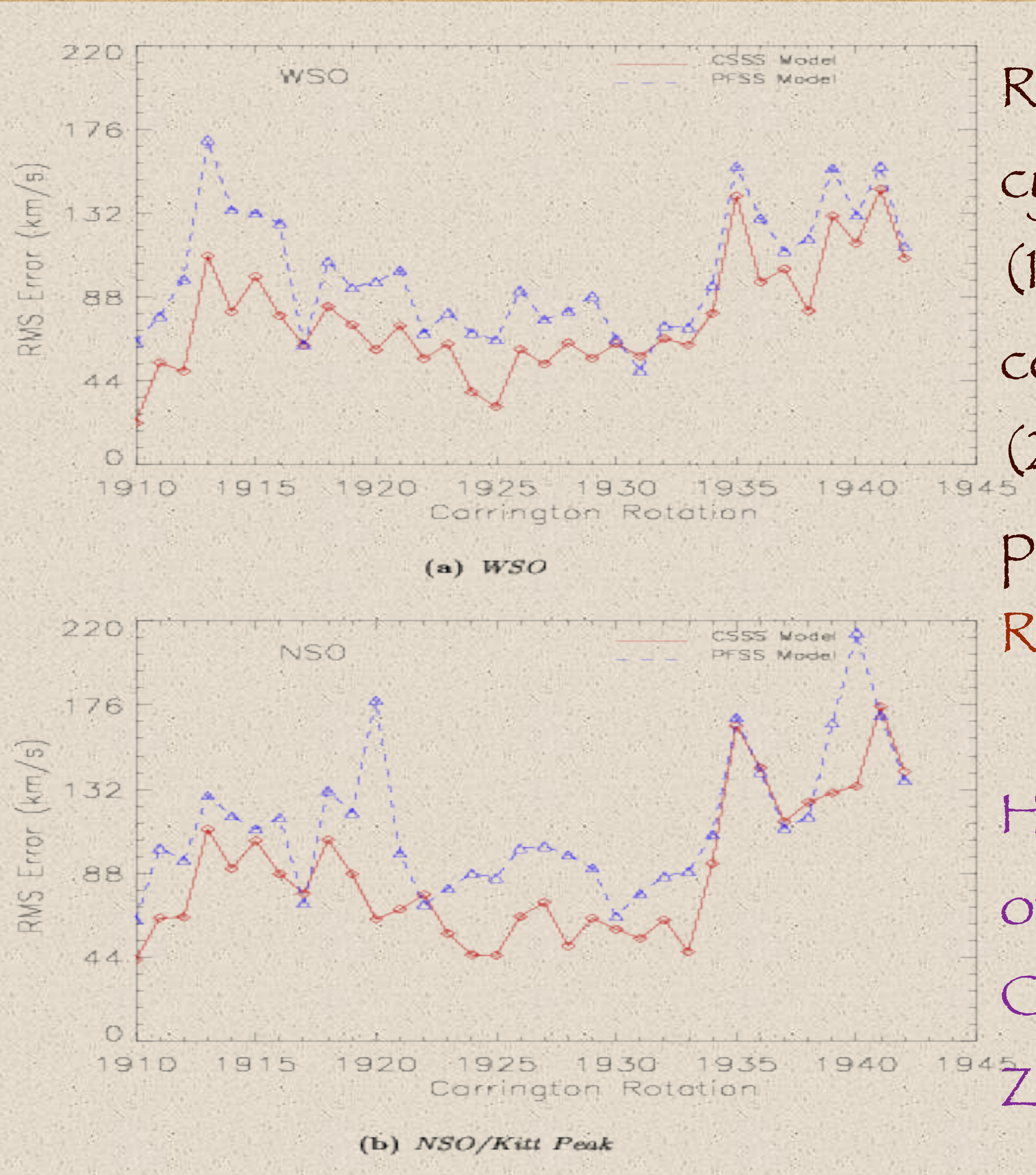
(a) WSO



(b) NSO/Kitt Peak



(c) WSA/ENLIL using NSO



RMSE increases as solar cycle progresses —>
(1) difficulty modelling complex magnetic field.
(2) Optimization of free parameters:

R_{SS} = 15 Rsun or closer?

R_{cp} = 2.5 Rsun?

Height of cusp varies over wide range (see, e.g. Cranmer et al., 2007 Zhao & Hoeksema, 1995)

Skill scores

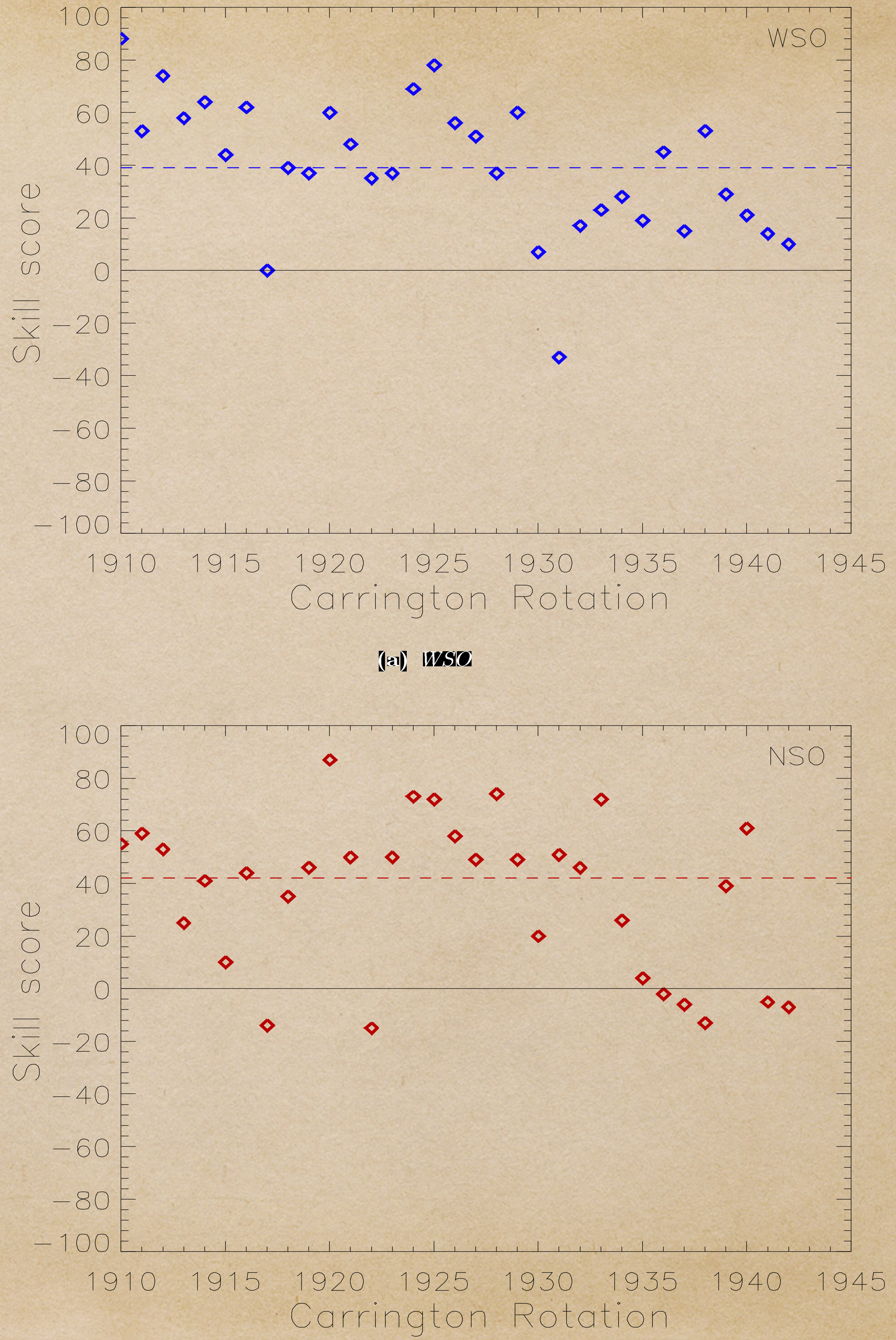
- comparable

NSO

(mean 42)

better than WSO

(mean 39)



CONCLUDING REMARKS

For a given synoptic map:

CSSS model performs 1.5 – 2 times better than PFSS and WSA/ENLIL

taking RMS error as the metric of accuracy

With high resolution, high quality HMI data, CSSS predictions will be more accurate

CONCLUDING REMARKS

to establish **Sun - Solar wind connectivity:**

mapped observed solar wind back to corona and predicted speed using magnetic field properties at the foot points represented by FTE

PFSS: solar wind mapped back to 2.5 R_{sun}

CSSS: 15 R_{sun} — avoids the region below Alfven critical point - where SW is still accelerating

CONCLUDING REMARKS

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

CSSS: magnetic fields allowed to be nonradial between 2.5 R_{sun} and 15 R_{sun}

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

CONCLUDING REMARKS

source surface location in the CSSS model is free to vary — a great advantage — can be placed outside Alfven critical point

the coronal and heliospheric magnetic field strengths can be computed/predicted and compared with in situ measurements

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