More Solar Wind Predictions Using Coronal Extrapolation models

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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 IMF and solar wind speed

SOLAR WIND ORIGIN

Fast wind: coronal holes - open magnetic field region
(> 450 km/s)

Slow: near streamers – closed magnetic field
(< 450 km/s)

Y. M. Wang & N. R. 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

WHY CORONAL MODELS?

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

TWO MODELS

Potential Field Source Surface (PFSS) model

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

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

Current Sheet Source Surface (CSSS) model

CSSS MODEL

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

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

and

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

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

using spherical harmonic expansion and source surface technique

Zhao & Hoeksema, (JGR, 100, 99, 1995)

developed CSSS model

includes - volume & sheet currents

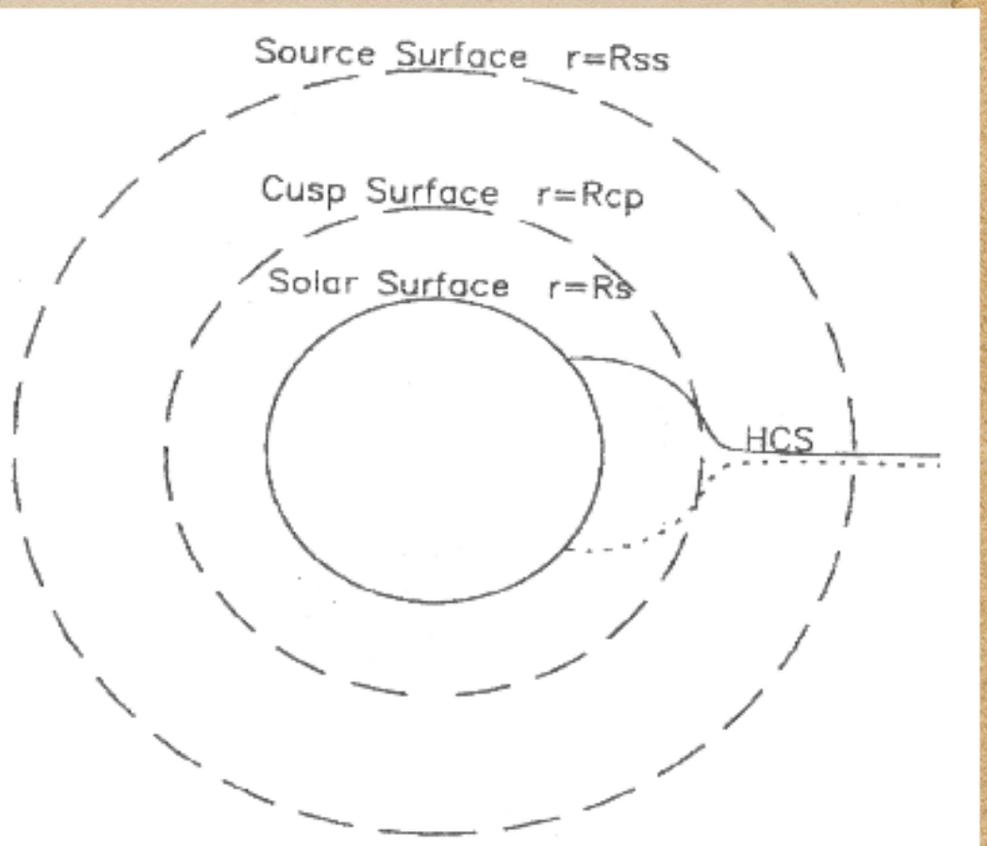
- source surface

CSSS MODEL - GEOMETRY

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

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

SOLAR WIND PREDICTION

- used CSSS and PFSS models to compute FTE
- used the speed-FTE relationship of Wang & Sheeley to predict solar wind speed

DATA

- Daily averaged solar wind data 1996-2010

solar cycles 23, 24

- Photospheric synoptic maps

SOHO/MDI 1° lat-lon

MDI data not available outside of this period

METHOD-Step 1

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-Steps 2-4

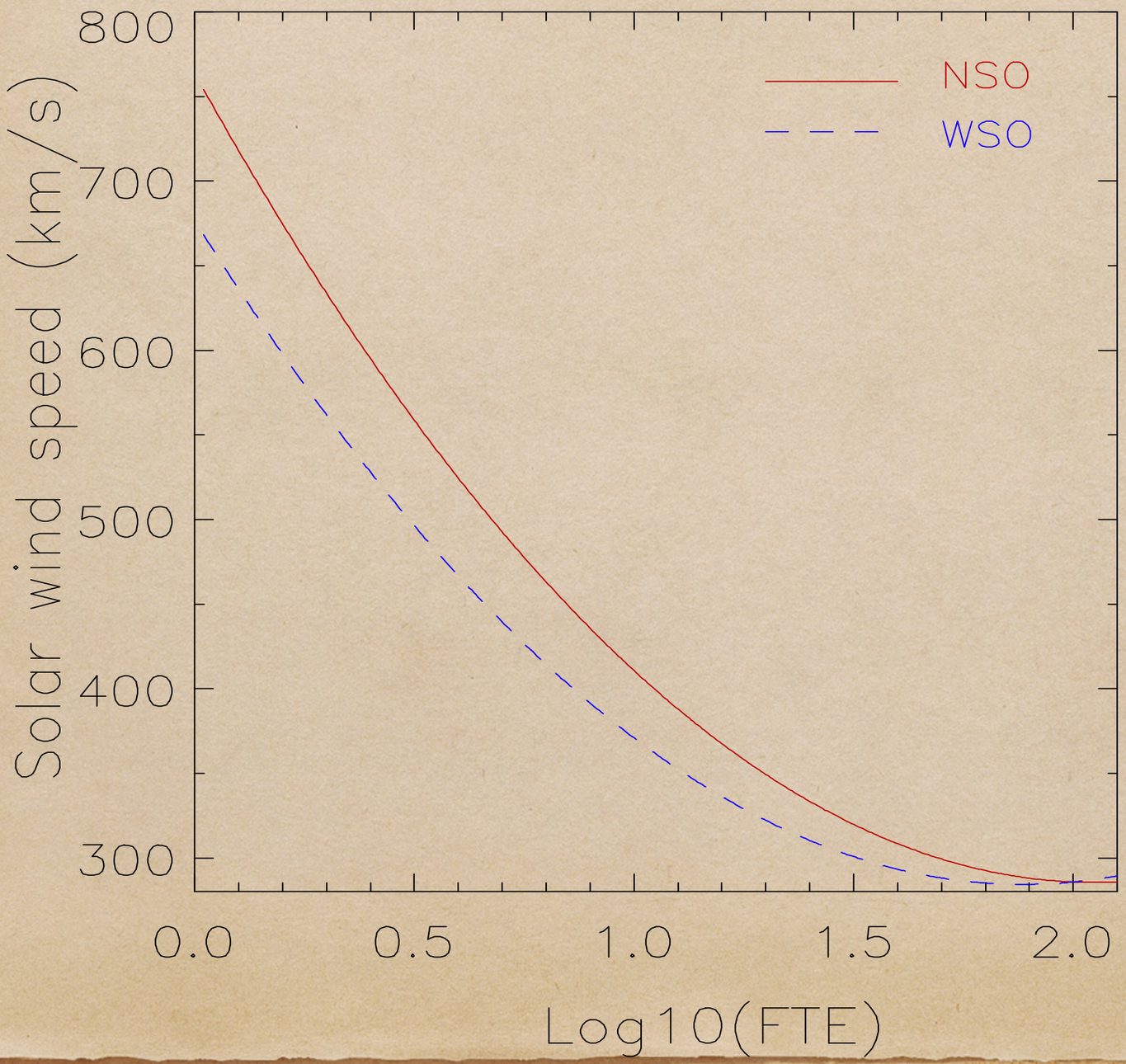
Step 2: map coronal location back to photosphere along open field lines using CSSS & PFSS models

Step 3: compute FTE at each solar wind source location

Step 4: 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

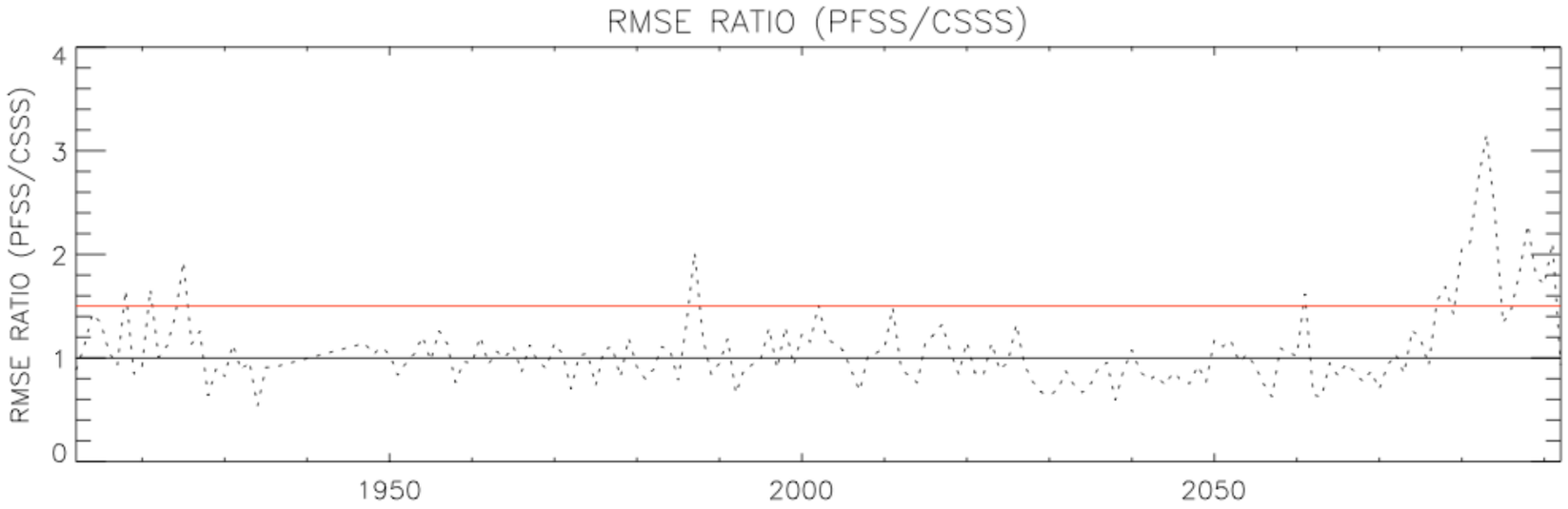
- the quadratic function is used for all the subsequent solar wind speed predictions
- used the same functional form for both PFSS and CSSS models

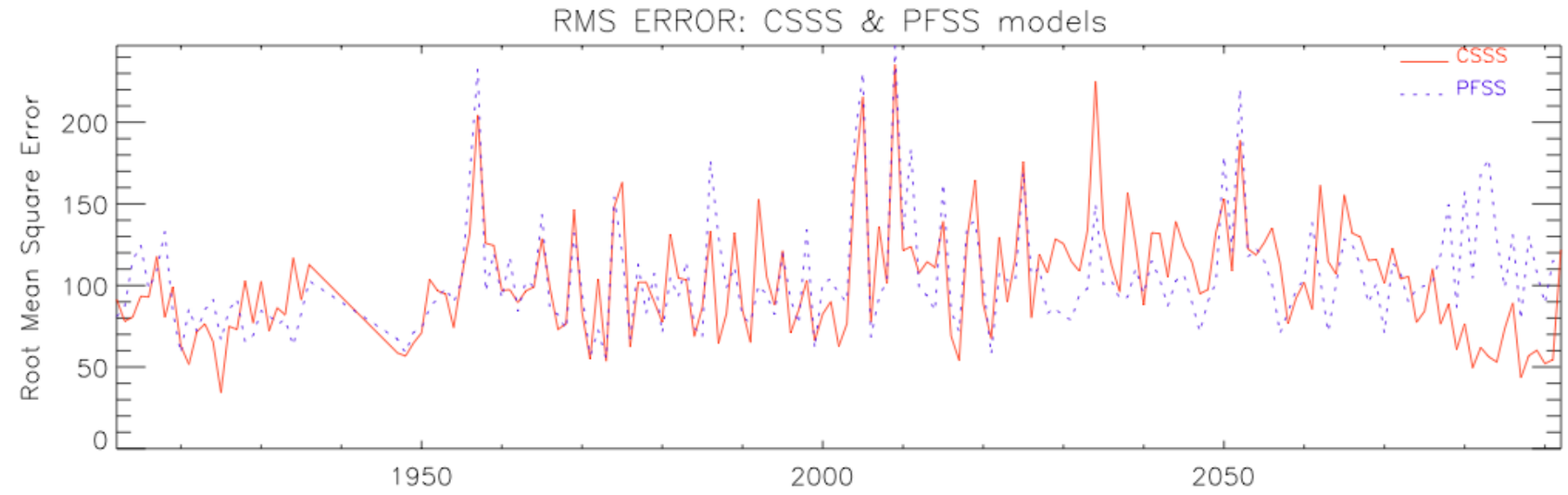
RMSE

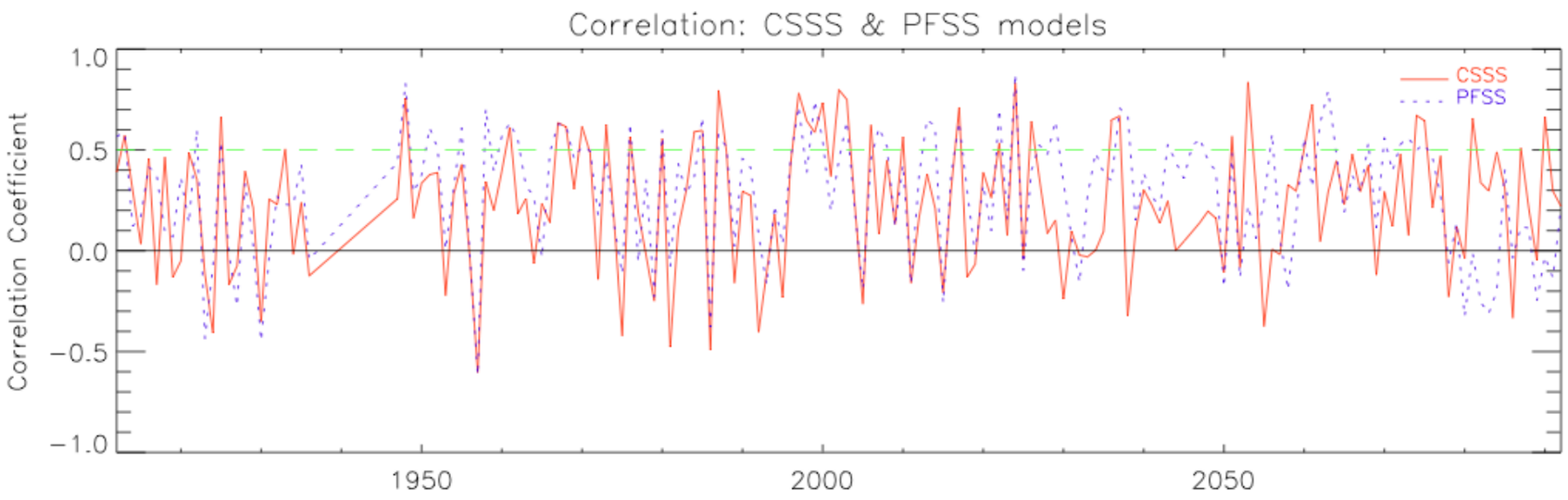
Evaluate performances of PFSS and CSSS models

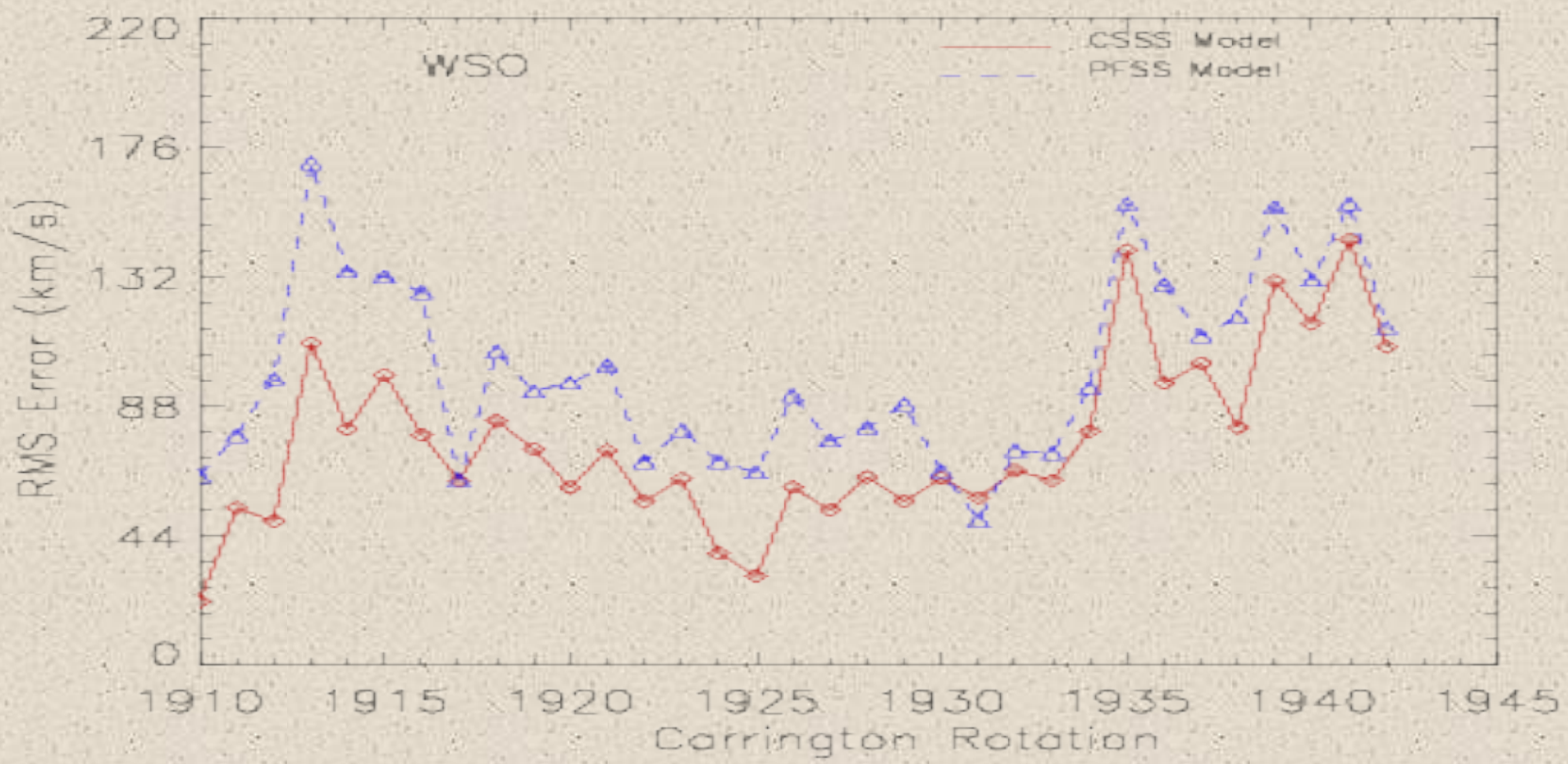
Root Mean Square Error (RMSE)
between observed and predicted speeds

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

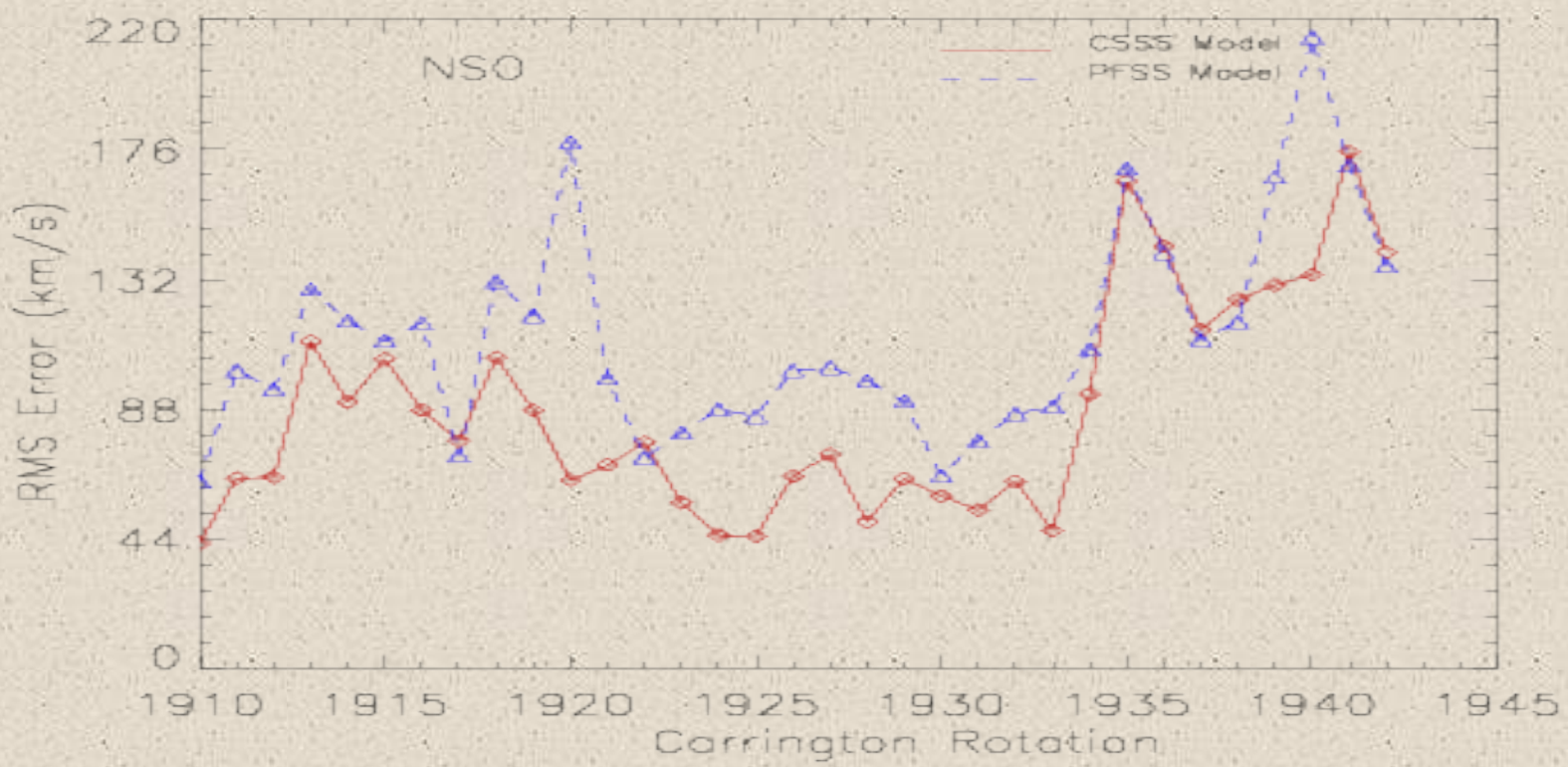

RMSE RATIO (PFSS/CSSS)
RMSE RATIO (PFSS/CSSS)
0
1
2
3
4
1950
2000
2050


RMS ERROR: CSSS & PFSS models
Root Mean Square Error
0
50
100
150
200
1950
2000
2050
CSSS
PFSS


Correlation: CSSS & PFSS models
Correlation Coefficient
−1.0
−0.5
0.0
0.5
1.0
1950
2000
2050
CSSS
PFSS



(a) *WSO*



(b) *NSO/Kitt Peak*

RMSE increases as solar cycle progresses —>

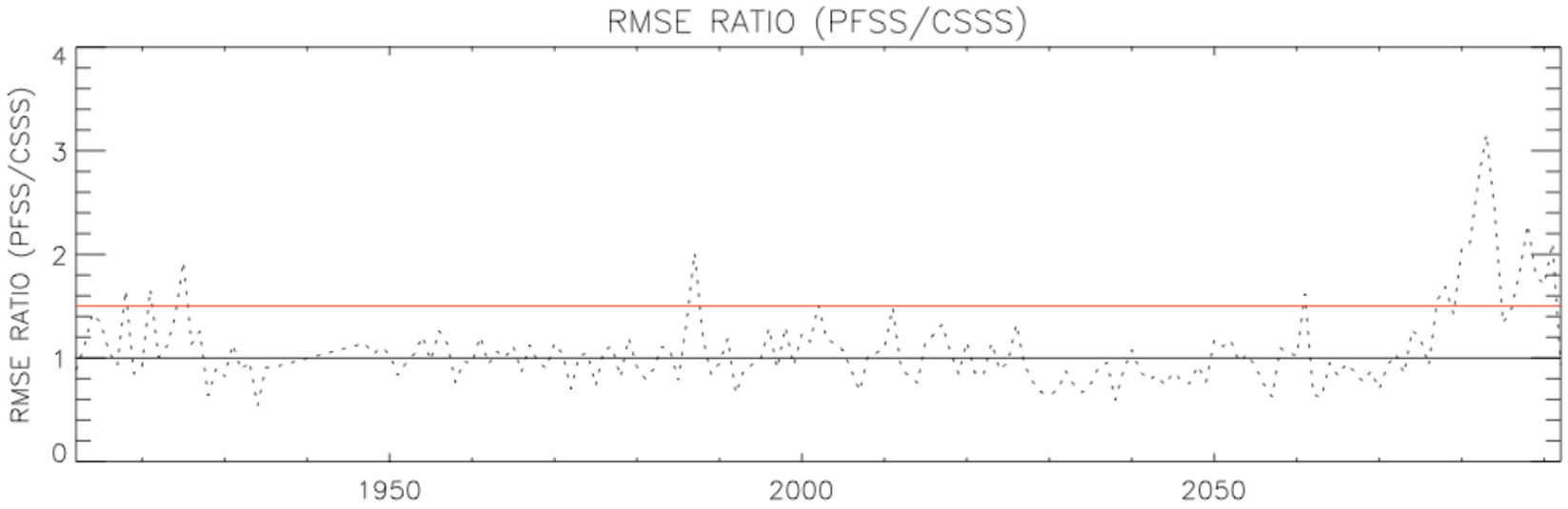
(1) difficulty modelling complex magnetic field.

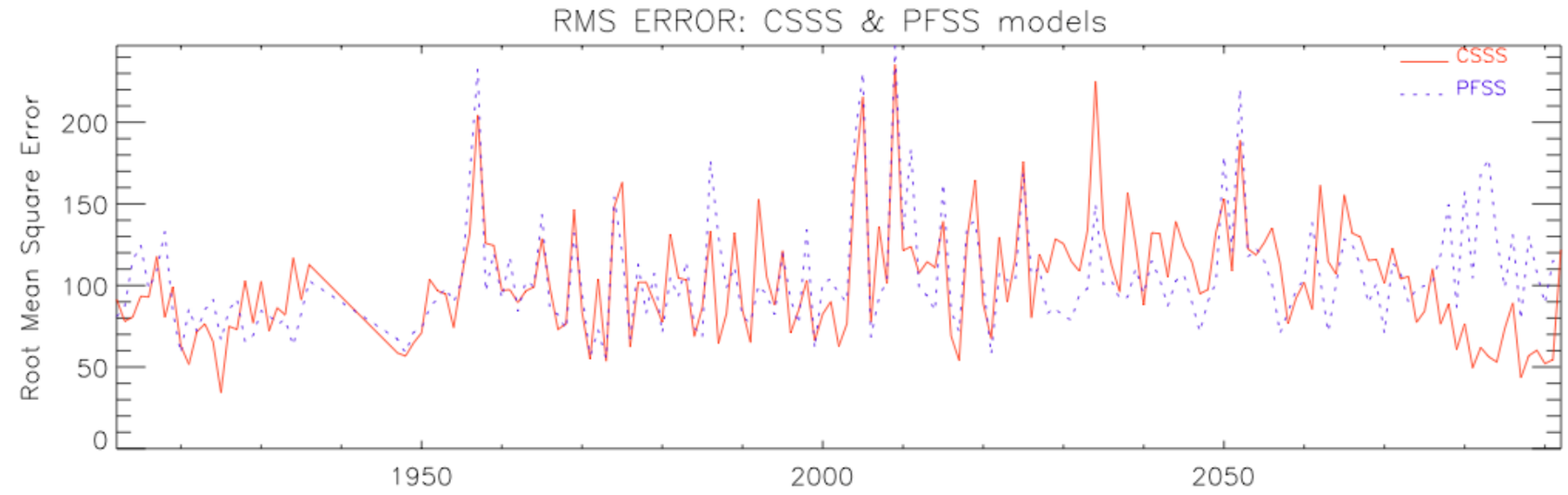
(2) Optimization of free parameters:

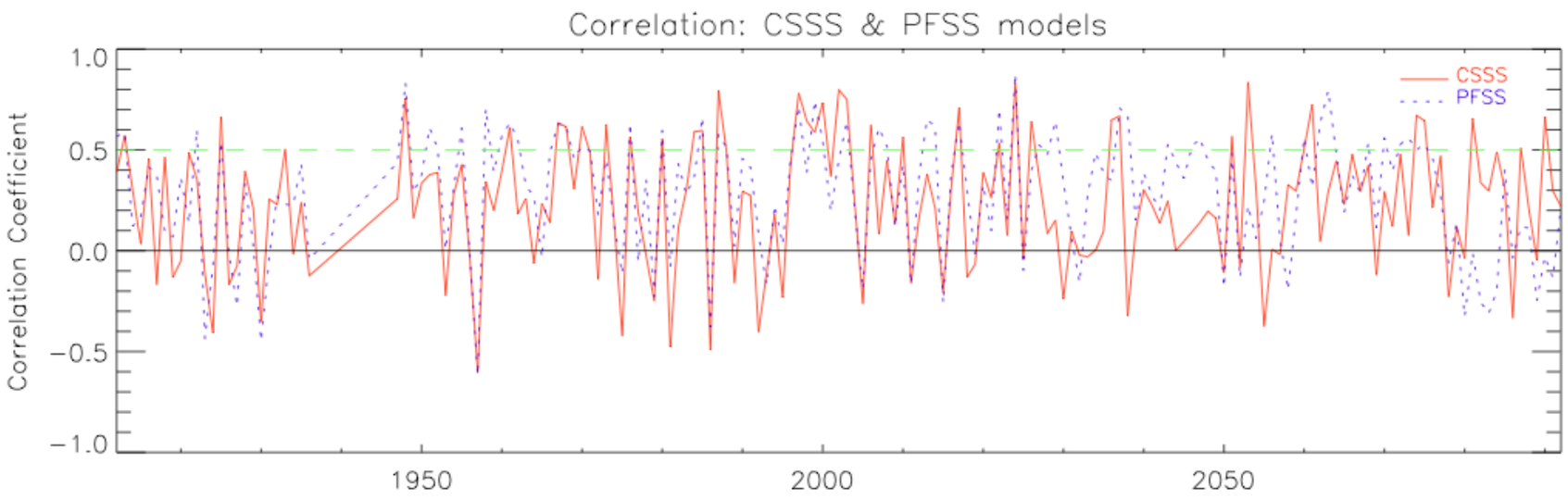
R_{SS} = 15 Rsun or closer?

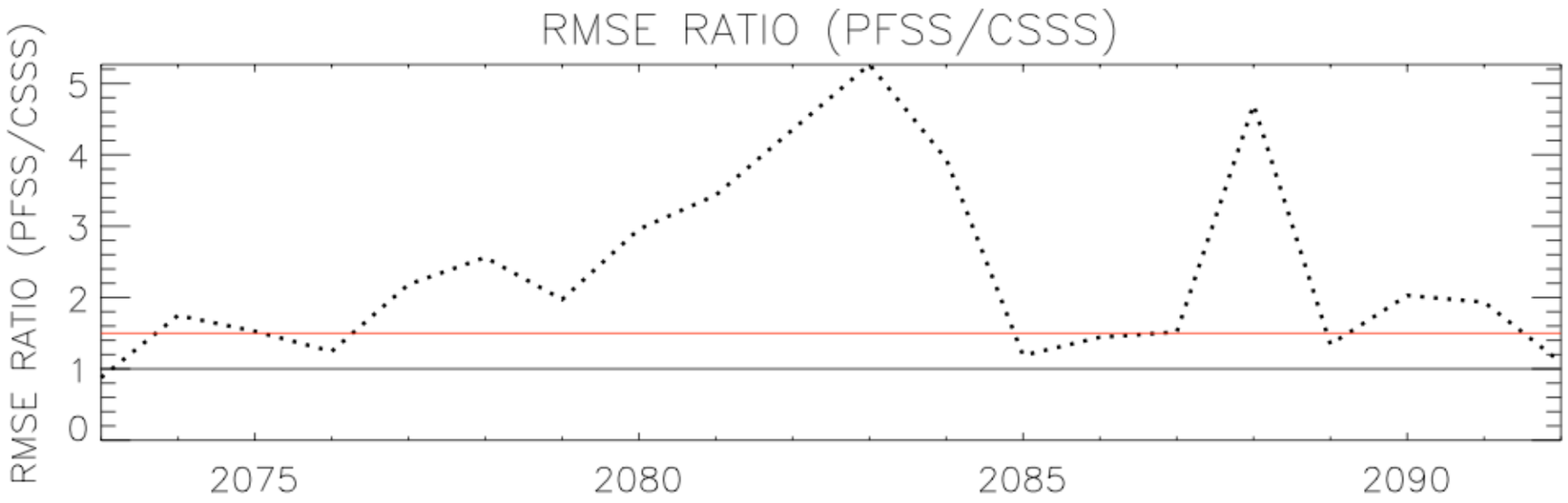
R_{CP} = 2.5 Rsun?

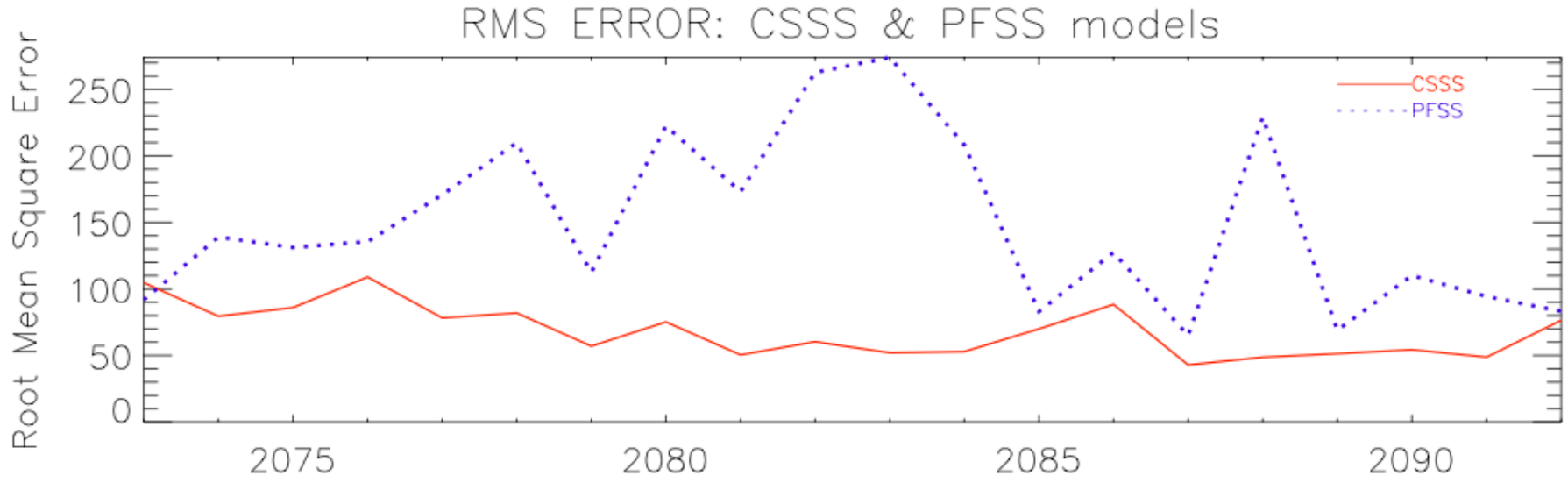
Height of cusp varies over wide range (see, e.g. Cranmer et al., 2007 Zhao & Hoeksema, 1995)

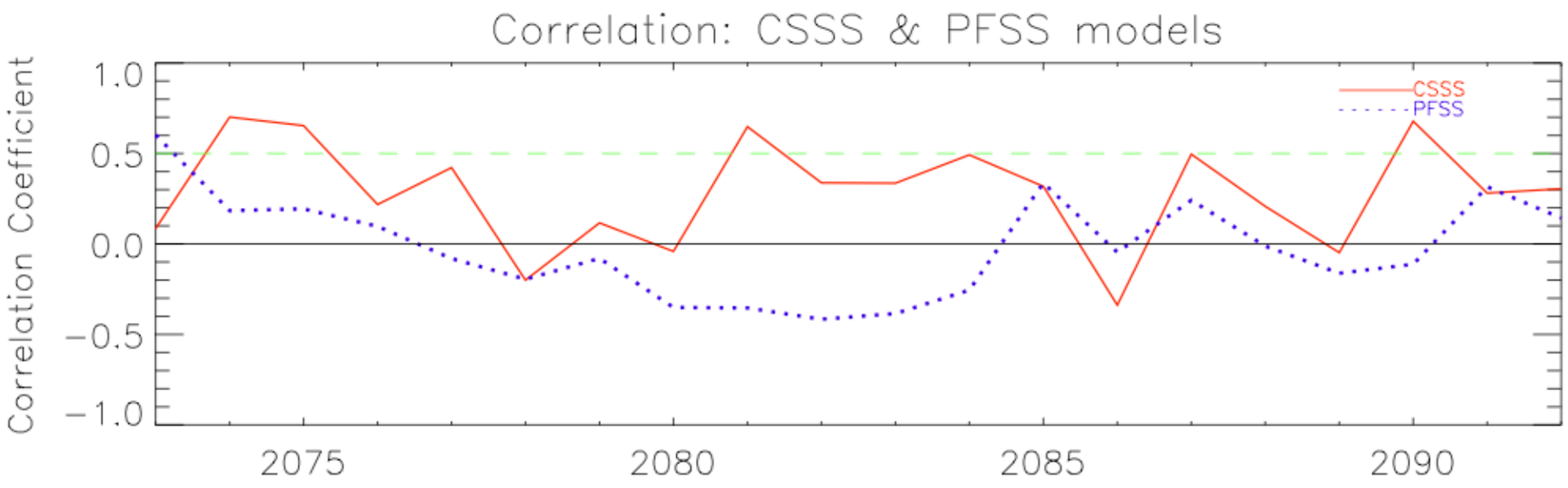

RMSE RATIO (PFSS/CSSS)
RMSE RATIO (PFSS/CSSS)
0
1
2
3
4
1950
2000
2050

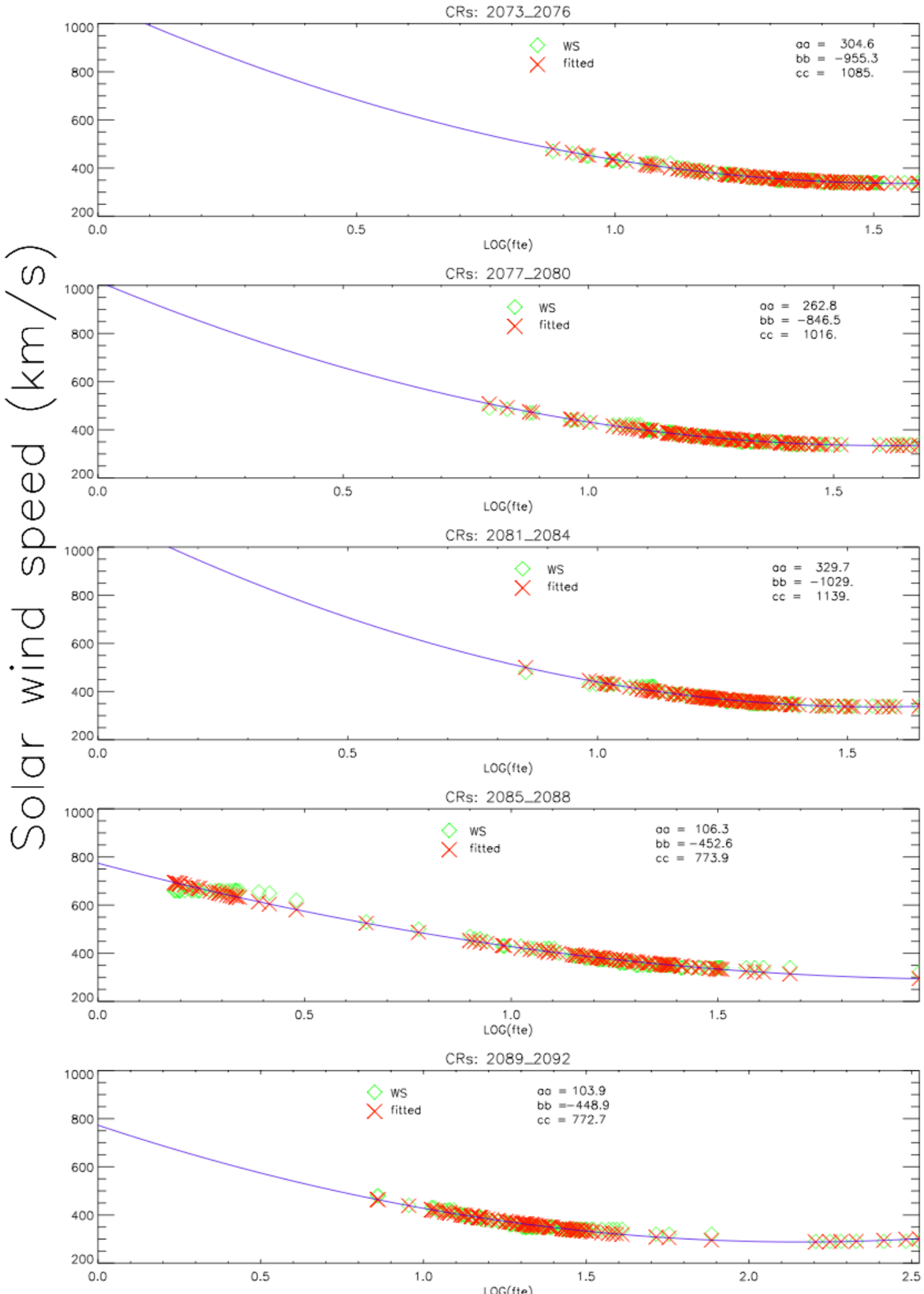

RMS ERROR: CSSS & PFSS models
Root Mean Square Error
0
50
100
150
200
1950
2000
2050
CSSS
PFSS


Correlation: CSSS & PFSS models
Correlation Coefficient
−1.0
−0.5
0.0
0.5
1.0
1950
2000
2050
CSSS
PFSS

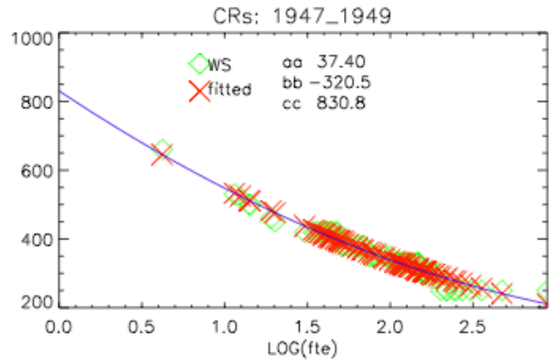

RMSE RATIO (PFSS/CSSS)
RMSE RATIO (PFSS/CSSS)
0
1
2
3
4
5
2075
2080
2085
2090

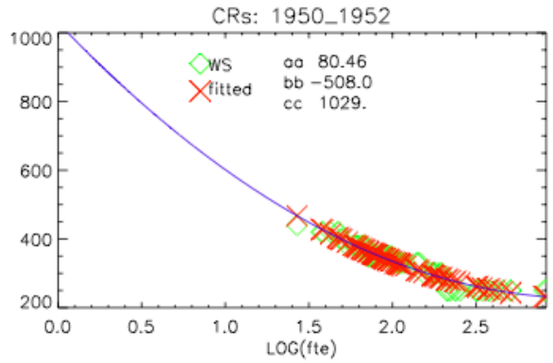

RMS ERROR: CSSS & PFSS models
Root Mean Square Error
0
50
100
150
200
250
CSSS
PFSS
2075
2080
2085
2090

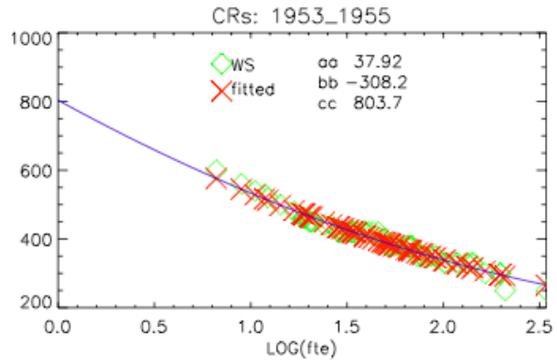

Correlation: CSSS & PFSS models
Correlation Coefficient
−1.0
−0.5
0.0
0.5
1.0
CSSS
PFSS
2075
2080
2085
2090

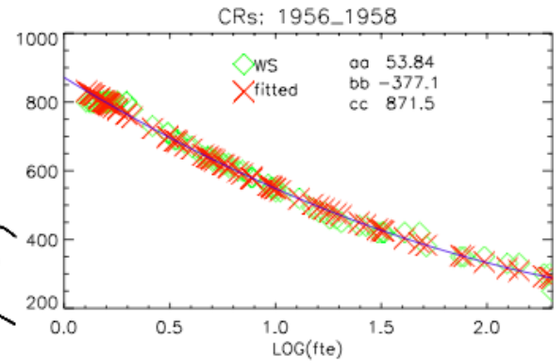

CRs: 2073_2076
WS
fitted
aa = 304.6
bb = −955.3
cc = 1085.
CRs: 2077_2080
WS
fitted
aa = 262.8
bb = −846.5
cc = 1016.
CRs: 2081_2084
WS
fitted
aa = 329.7
bb = −1029.
cc = 1139.
CRs: 2085_2088
WS
fitted
aa = 106.3
bb = −452.6
cc = 773.9
CRs: 2089_2092
WS
fitted
aa = 103.9
bb = −448.9
cc = 772.7
Solar wind speed (km/s)
LOG(fte)

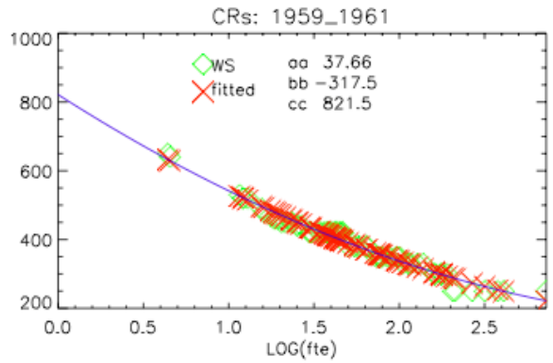
Solar wind speed (km/s)

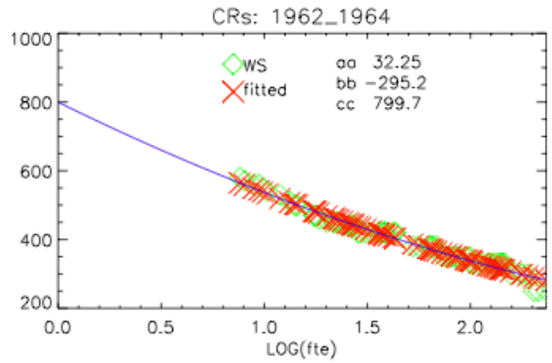


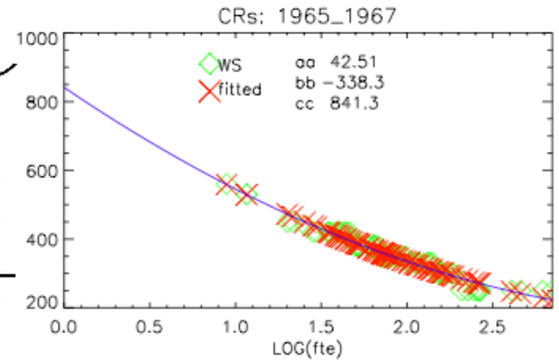


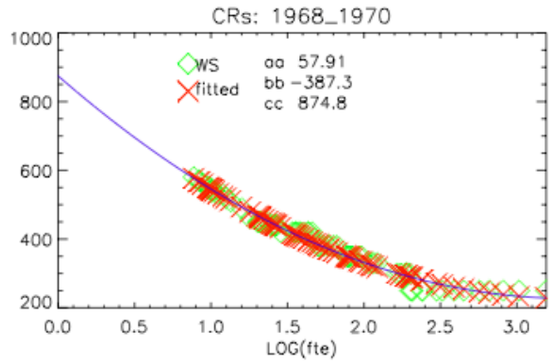


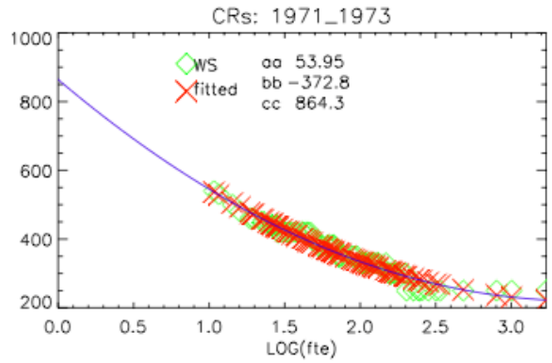


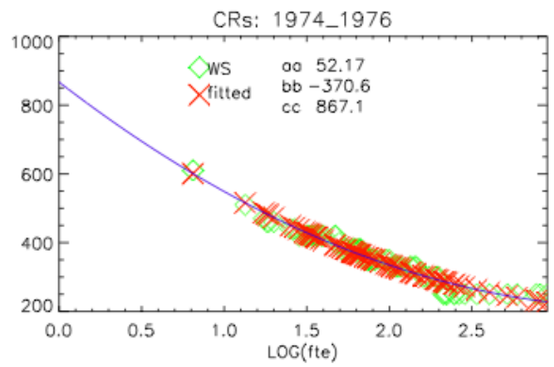


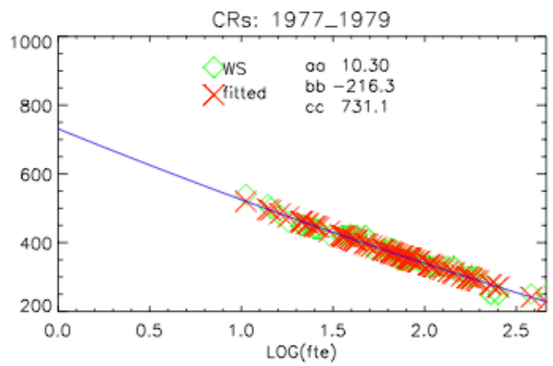


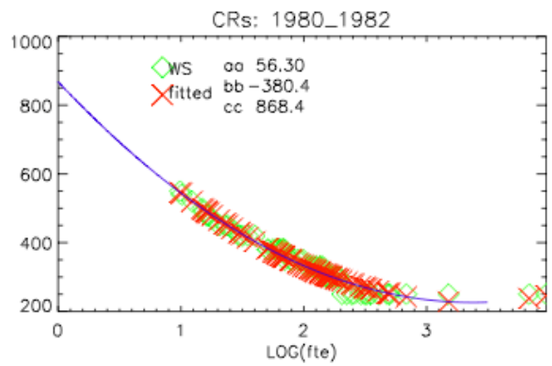


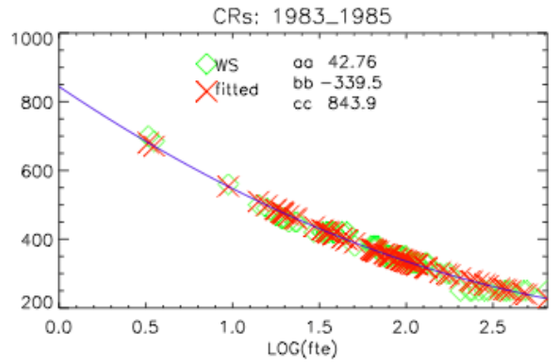






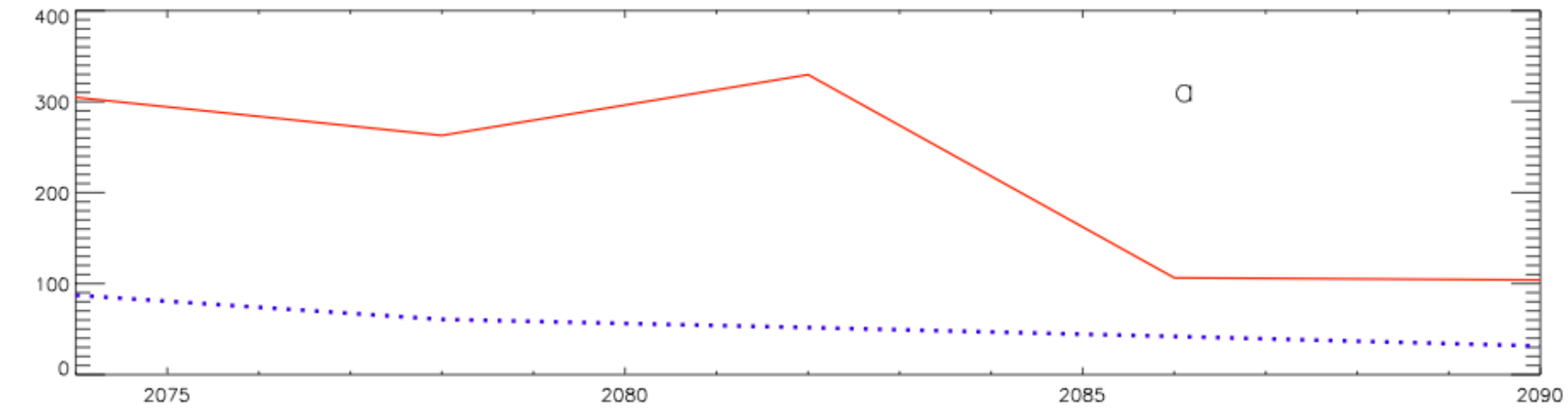






Bala

2016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300
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2080
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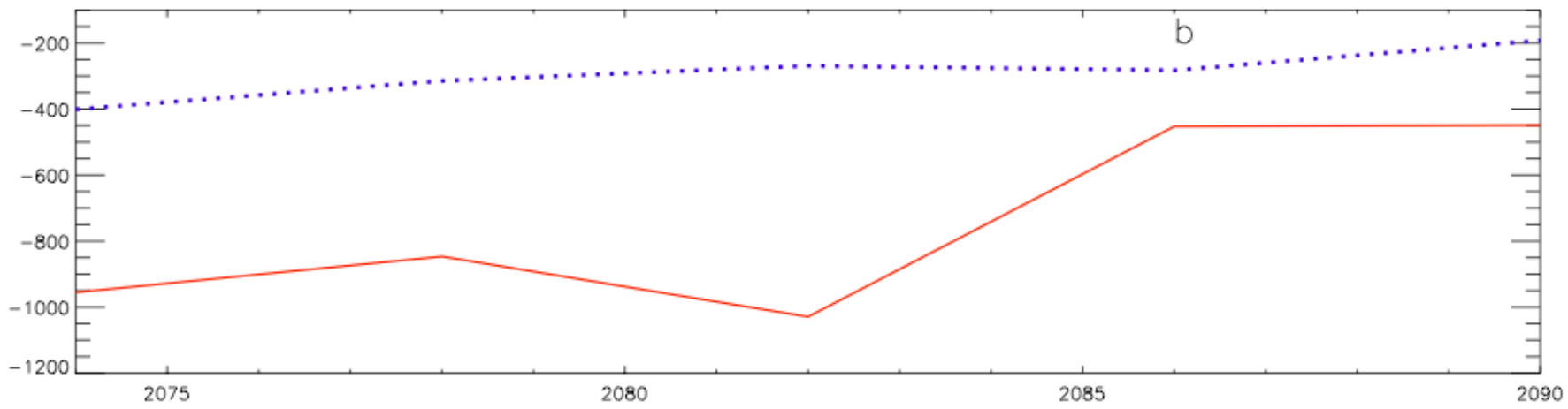
a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−1000
−1200
2075
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2085
2090
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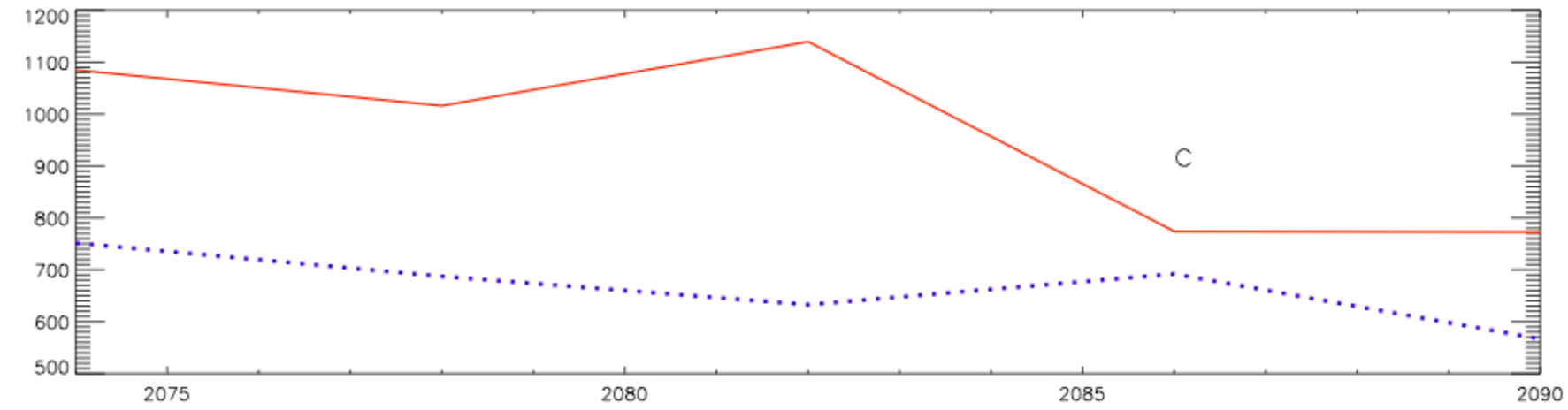
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900
800
700
600
500
2075
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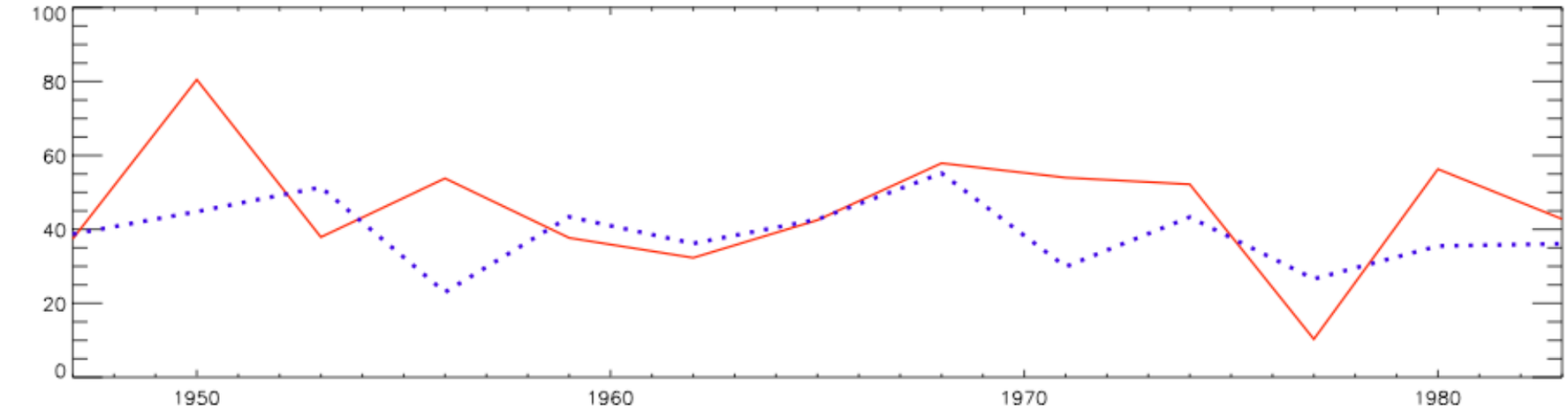
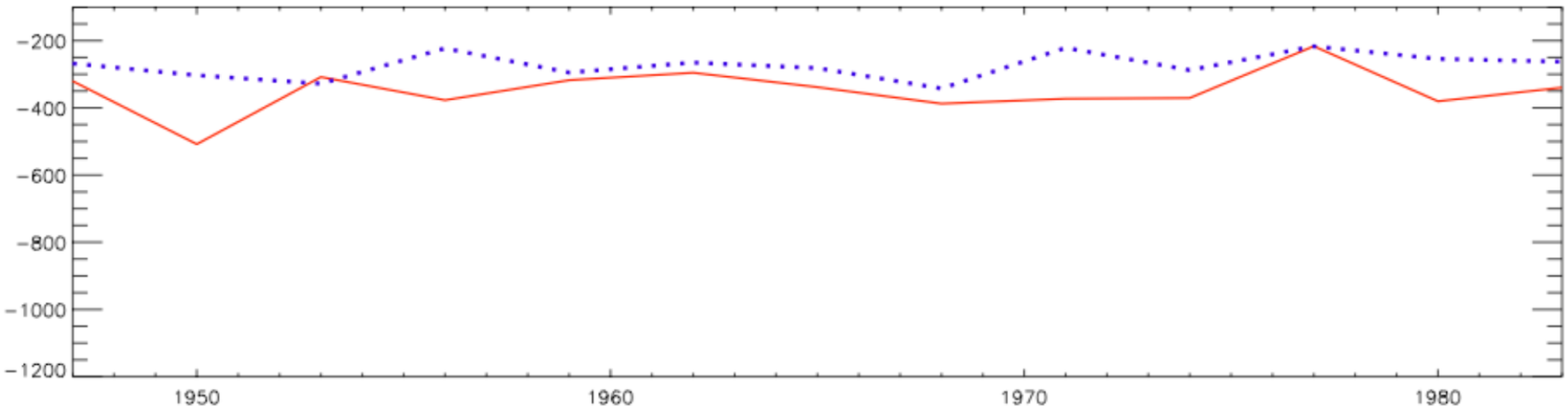
2085
2090
C


100
80
60
40
20
0
1950
1960
1970
1980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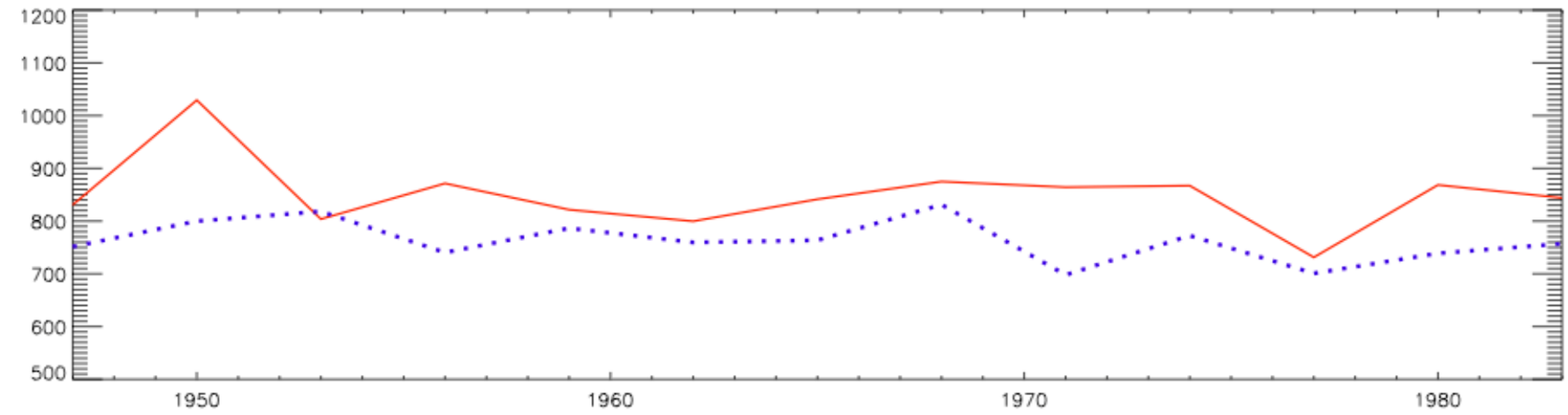
−400
−600
−800
−1000
−1200
1950
1960
1970
1980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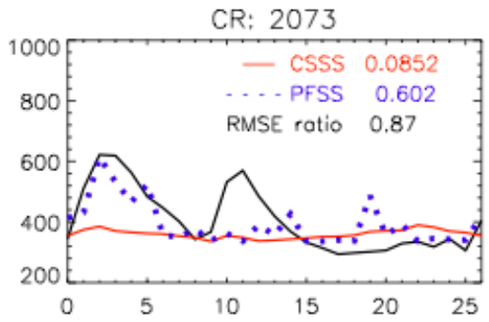
1950
1960
1970
1980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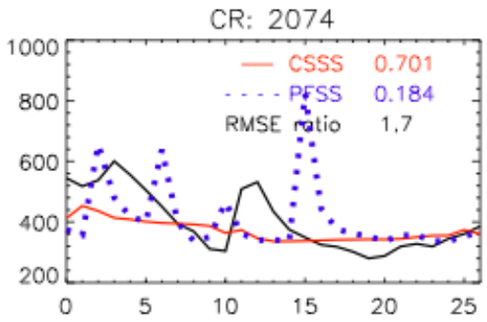
CSSS 0.0852
PFSS 0.602
RMSE ratio 0.87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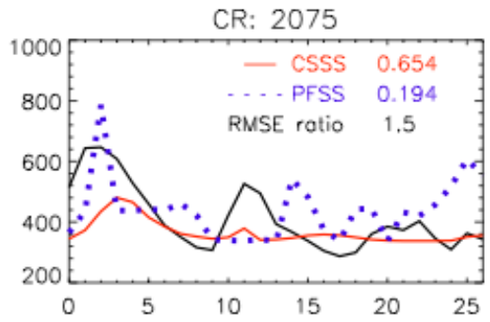
PFSS 0.184
RMSE ratio 1.7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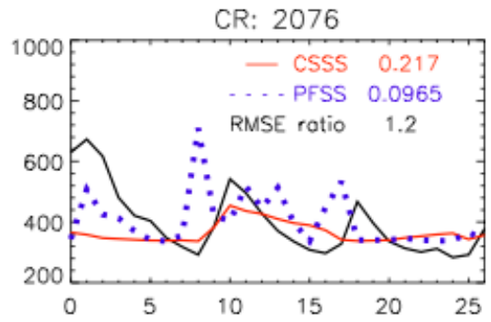
PFSS 0.194
RMSE ratio 1.5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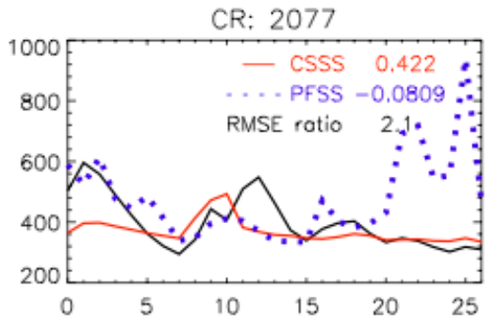
RMSE ratio 1.2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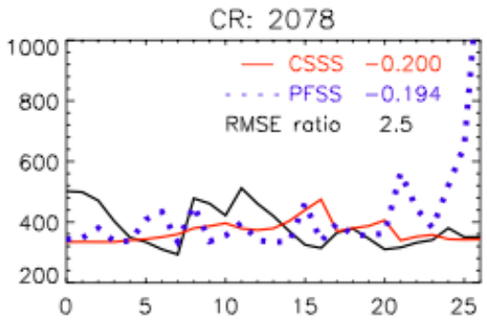
PFSS −0.0809
RMSE ratio 2.1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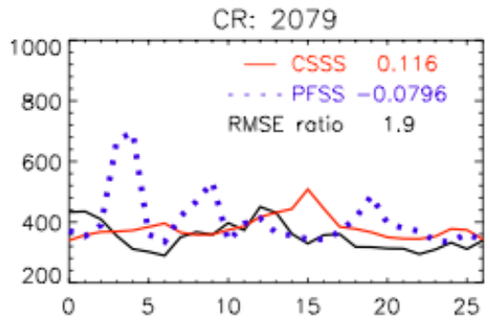
RMSE ratio 2.5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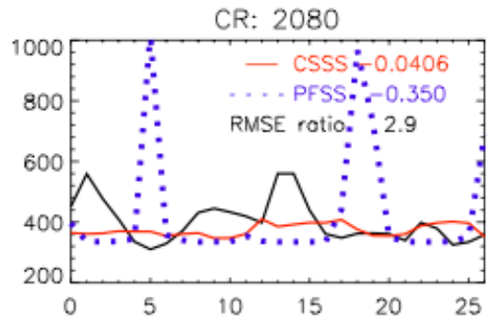
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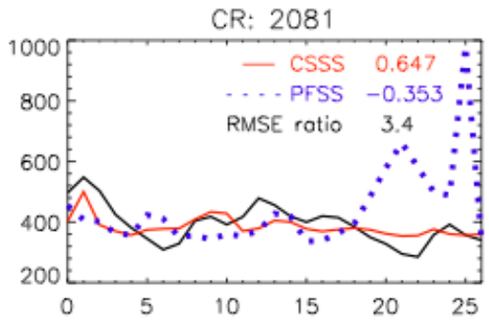
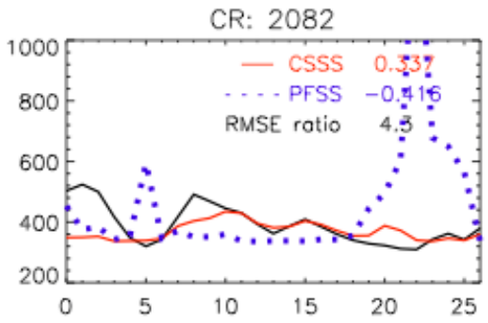
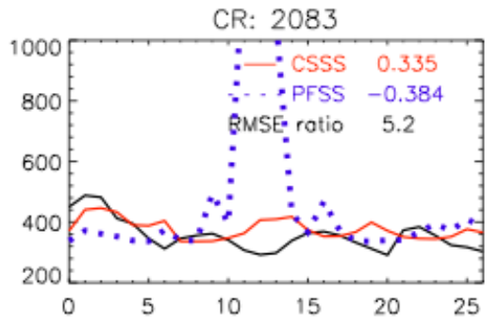
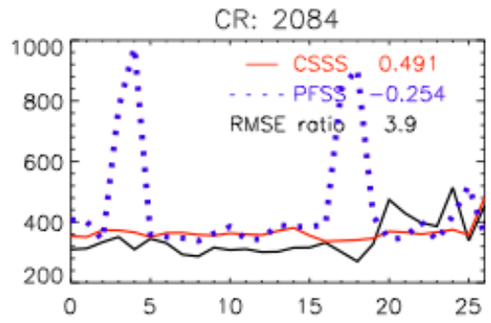
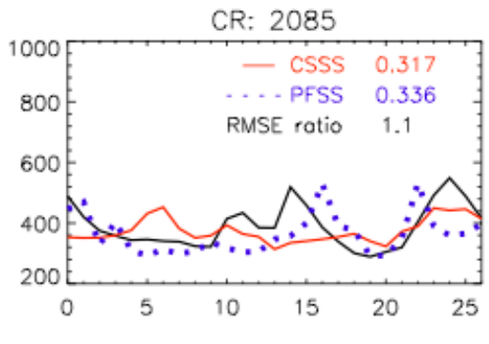
CSSS −0.0406
PFSS −0.350
RMSE ratio 2.9

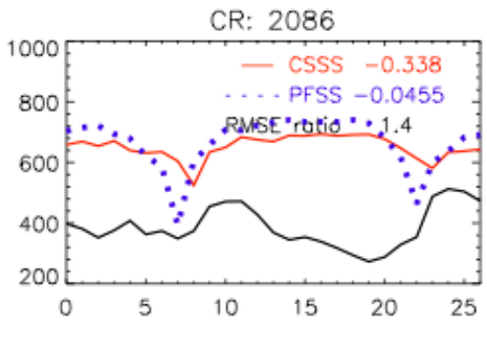

CR: 2081
CSSS 0.647
PFSS −0.353
RMSE ratio 3.4

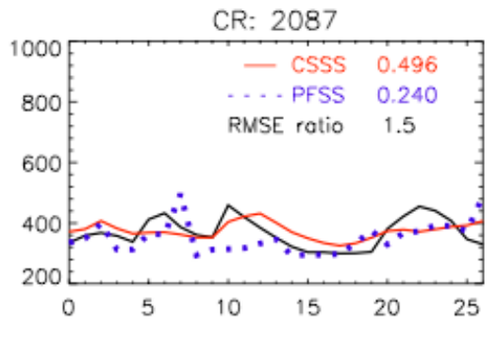

CR: 2082
CSSS 0.337
PFSS −0.116
RMSE ratio 4.3

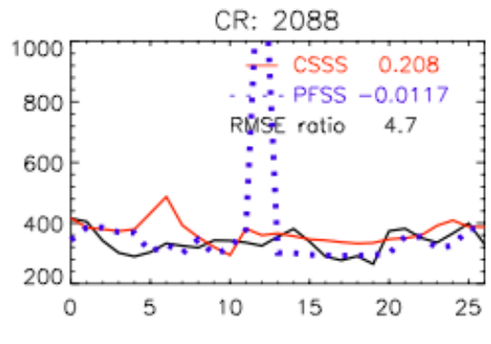

CR: 2083
CSSS 0.335
PFSS −0.384
RMSE ratio 5.2

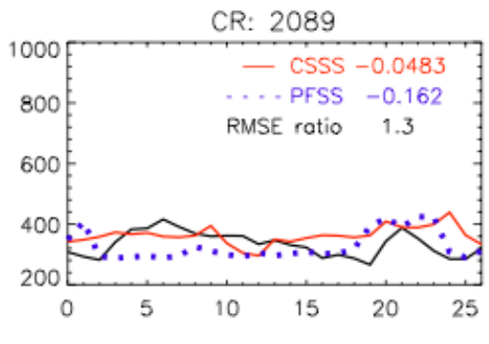

CR: 2084
CSSS 0.491
PFSS −0.254
RMSE ratio 3.9

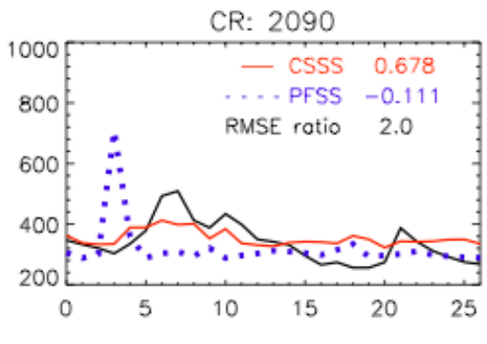

CR: 2085
CSSS 0.317
PFSS 0.336
RMSE ratio 1.1

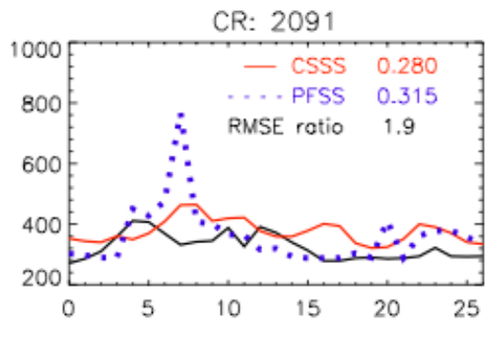

CR: 2086
CSSS −0.338
PFSS −0.0455
RMSE ratio 1.4

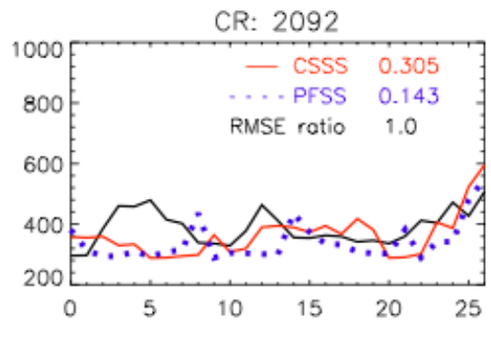

CR: 2087
CSSS 0.496
PFSS 0.240
RMSE ratio 1.5


CR: 2088
CSSS 0.208
PFSS −0.0117
RMSE ratio 4.7


CR: 2089
CSSS −0.0483
PFSS −0.162
RMSE ratio 1.3


CR: 2090
CSSS 0.678
PFSS −0.111
RMSE ratio 2.0


CR: 2091
CSSS 0.280
PFSS 0.315
RMSE ratio 1.9


CR: 2092
CSSS 0.305
PFSS 0.143
RMSE ratio 1.0

CONCLUDING REMARKS

Investigation of the controlling influence of magnetic field on solar wind outflow.

$$FTE = Br(pho)/Br(ss) * (R/Rss)^2$$

Br(pho); R: photospheric magnetic field & radius

Br(ss), Rss: source surface magnetic field & radius

CONCLUDING REMARKS

~solar cycle variation ~ quadratic term in the best fit to speed-FTE

~nearly disappearing during certain solar rotations,

~ giving rise to an almost linear fit ~

~this variation is significant in CSSS model

~nearly negligible in PFSS model

How this information can be used to deduce the influence of magnetic field on solar wind outflow is being investigated further.

CONCLUDING REMARKS

Solar Orbiter & Solar Probe Plus provide information on coronal conditions within 40 R_{sun} — CSSS predictions will be useful in interpreting the results …