Naval Research Laboratory (NRL) Version 2 Solar Irradiance Variability Model

Methodology, Uncertainty Estimation, Operational Algorithm, Differences from Original model

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Section 1: Model Formulation

Model Formulation

- The magnitude of the irradiance changes from Quiet Sun conditions are determined from multiple linear regression analysis of observations and proxy records of magnetic variability.

Quiet Sun reference spectrum is based on SORCE measurements

[Woods et al. 2009; Kopp and Lean, 2011].

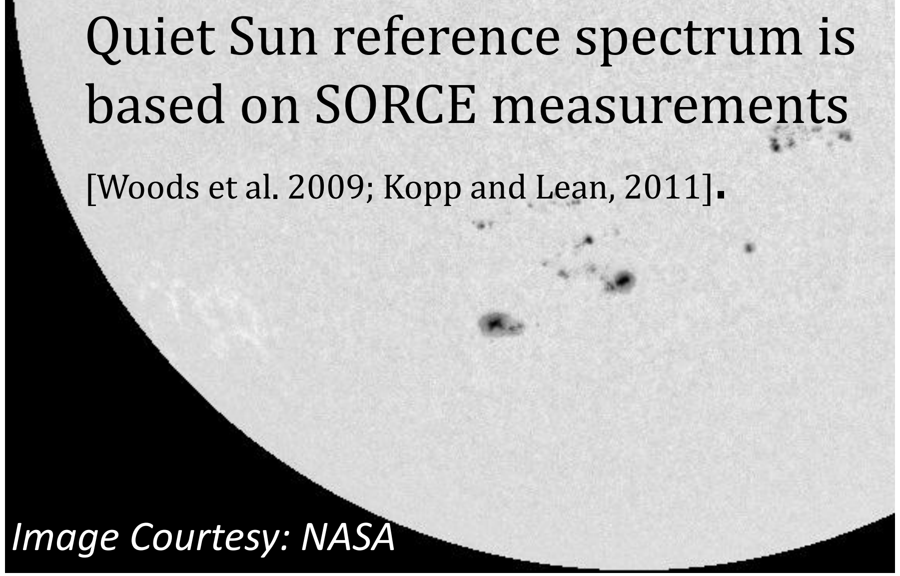
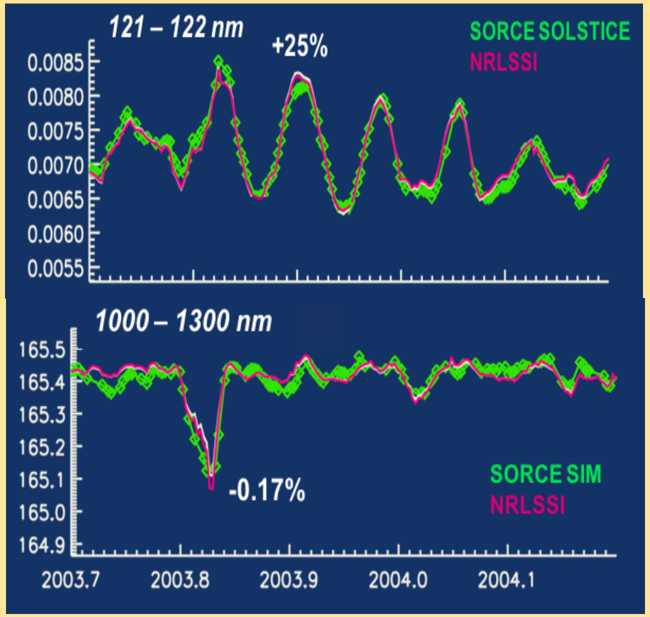
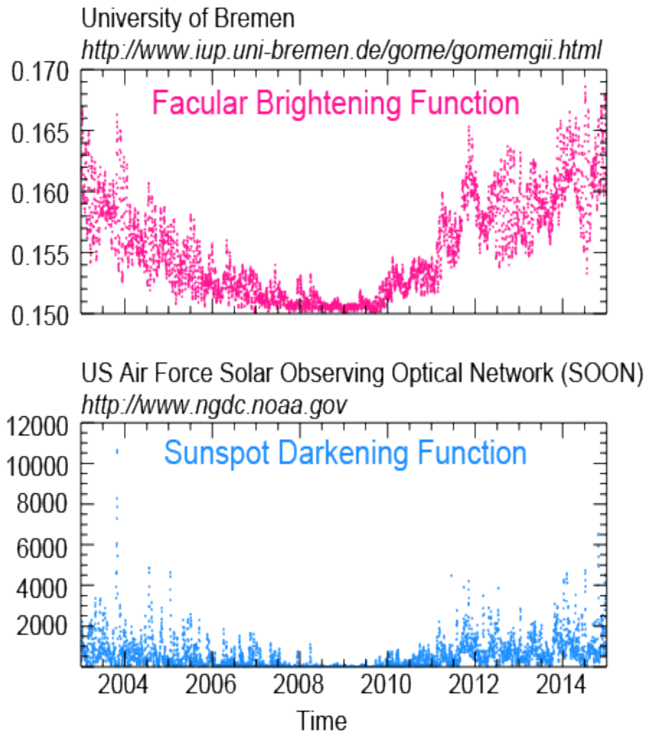


Image Courtesy: NASA

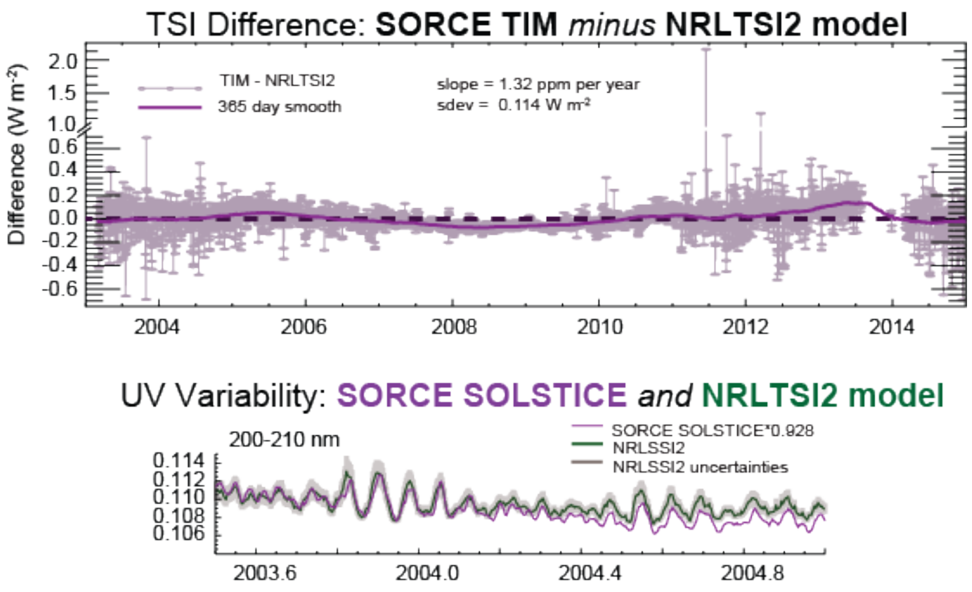
6 month Variability

observations and NRL (original)





NRL (version 2) Results



Coddington et al., 2016, *BAMS*

*For NRL model version 2, SORCE SSI data are *detrended* prior to regression analysis because the observed solar cycle variability conflicts with theory and models [Lean and Deland, 2012; Yeo et al, 2014].

SORCE TSI contributions to NRLTSI2

- NRLTSI2 regression coefficients to scale facular brightening and sunspot darkening to TSI are derived from ~ 11 years of SORCE TIM observations (with proxies of facular brightening and sunspot darkening for the same time frame).

- Facular brightening proxy = Univ. of Bremen Composite Mg II index
- Sunspot darkening proxy = USAF SOON sunspot area and location

Algorithm Overview

- NRLTSI2 is a proxy model that determines changes from quiet Sun conditions due to bright faculae (F) and dark sunspots (S) on the solar disk.

$$T(t) = T_Q \; + \; \Delta T_F(t) + \Delta T_S(t)$$

- Multiple linear regression analysis of the proxy indices of ‘F’ and ‘S’ with irradiance measurements determine the magnitude of irradiance change from background.

$$T_{mod}(t) = \; T_Q \; + a + \; b_F \times \left[F(t) - F_Q\right] + b_S \times \left[S(t) - S_Q\right]$$

NRLTSI2 Error Estimation: Putting some numbers to it

$$T_{mod}(t) = T_Q + a + b_F \times [F(t) - F_Q] + b_S \times [S(t) - S_Q]$$

- The precision and accuracy of NRLTSI2 depends on:
  - Uncertainty in the absolute scale of the reference Quiet Sun.
  - Statistical uncertainties in the scaling coefficients.
  - Uncertainties in the facular brightening and sunspot darkening values.

* Modeled TSI uncertainties exceed SORCE TIM measurement uncertainties by ~ a factor of 4.
** The uncertainties in modeled TSI scale with solar activity.

Quantity	Value and Uncertainty
T_Q	1360.45 +/- 0.5 W m^{-2}
a	0.091 +/- 0.006 W m^{-2}
b_F	139.66 +/- 1.12
b_S	-0.000564 +/- 0.000005
$F(t) - F_Q$	0.0151 +/- 0.003 (20%)
$S(t) - S_Q$	10647 +/- 2129 (20%)
b_F x $[F(t) – F_Q]$	2.2 +/- 0.4 W m^{-2}
b_S x $[S(t) – S_Q]$	-6.0 +/- 1.2 W m^{-2}
$T_{mod}(t) - T_Q$	-3.8 +/- 1.6 Wm^{-2}
$T_{mod}(t)$	1356.64 +/- 2.1 Wm^{-2}

Example specific to 30 Oct 2003….

SORCE SSI (and TSI) contributions to NRLSSI2

- For NRLSSI2, regression coefficients are derived from SORCE SOLSTICE and SIM observations over *solar rotational time scales* (the ~ 11 year record was detrended by removing an 81-day running mean prior to the regression with the similarly detrended facular brightening and sunspot darkening proxies).

- Regression coefficients from detrended time series differ from those developed from solar-cycle time series…so, we need to do a correction to solar cycle time scales.

- We use SORCE TIM data to constrain this correction. Ratios of coefficients from regression with TIM data to that of detrended TIM data are used to adjust coefficients for SSI (for wavelengths > 295 nm).
- For wavelengths < 290 nm, adjustments to coefficients were made using Ca II K time series.

Algorithm for NRLSSI2 is similar to NRLTSI2...*but not quite.*

$$I(\lambda,t) = I(\lambda)_Q + \Delta I_F(\lambda,t) + \Delta I_S(\lambda,t)$$

$$\Delta I_F(\lambda,t) = c_F(\lambda) + d_F(\lambda)\times\left[F(t) - F_Q + \Delta F(t)\right]$$

$$\Delta I_S(\lambda,t) = c_S(\lambda) + d_S(\lambda)\times\left[S(t) - S_Q + \Delta S(t)\right]$$

$$d_F = d_F^{detrend}\left(\frac{b_F}{b_F^{detrend}}\right)$$

$$d_S = d_S^{detrend}\left(\frac{b_S}{b_F^{detrend}}\right)$$

$\Delta F(t)$ and $\Delta S(t)$ ensure that:

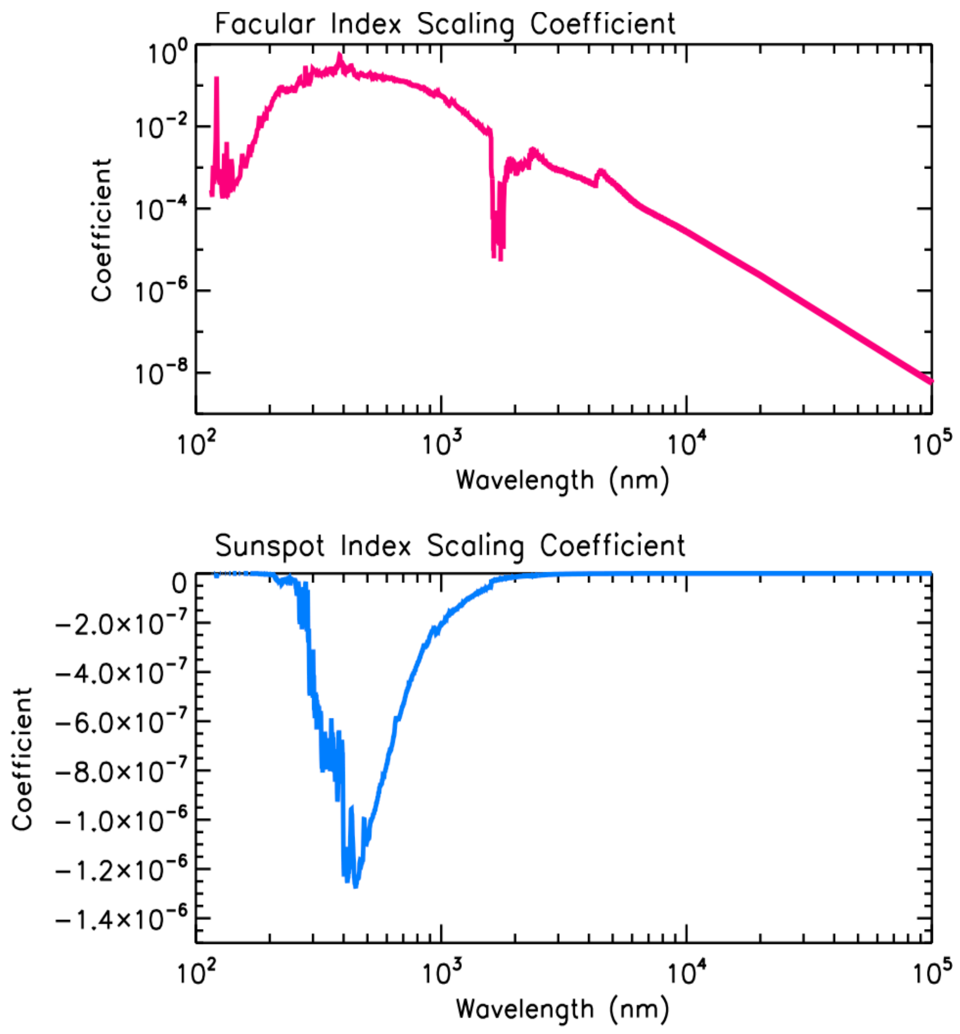
(Internal Consistency check)

$$T(t) = \int_{\lambda_0}^{\lambda_\infty} I(\lambda,t)\,d\lambda$$

$$\Delta T_F(t) = \int_{\lambda_0}^{\lambda_\infty} \Delta I_F(\lambda,t)\,d\lambda$$

$$\Delta T_s(t) = \int_{\lambda_0}^{\lambda_\infty} \Delta I_S(\lambda,t)\,d\lambda$$

Scaling coefficients for SSI model



$\Delta F(t)$

The value of *$\Delta F(t)$* is determined empirically by comparing the residual, *$R_{fac}(t)$*, of the integrated spectral irradiance facular brightening, evaluated initially with *$\Delta F(t)=0$*, with the total solar irradiance facular brightening i.e.,

$$R_{fac}(t) = a + b_F \times [F(t) - F_Q] - \sum (c_F(\lambda) + d_F(\lambda) \times [F(t) - F_Q])$$

then linearly relating this residual energy to the facular brightening index

$$R_{fac} = e_F \times [F(t) - F_Q]$$

from which the equivalent increment in the facular brightening index is determined as

$$\Delta F(t) = \frac{R_{fac}(t)}{b_F} = \frac{e_F \times [F(t) - F_Q]}{b_F}$$

$\Delta S(t)$

Similarly, $\Delta S(t)$ is determined empirically by comparing the residual, $R_{spot}(t)$, of the integrated spectral irradiance sunspot darkening evaluated initially with $\Delta S(t)=0$, with the total solar irradiance sunspot darkening i.e.,

$$R_{spot}(t) = b_S \times [S(t) - S_Q] - \sum (c_S(\lambda) + d_S(\lambda) \times [S(t) - S_Q])$$

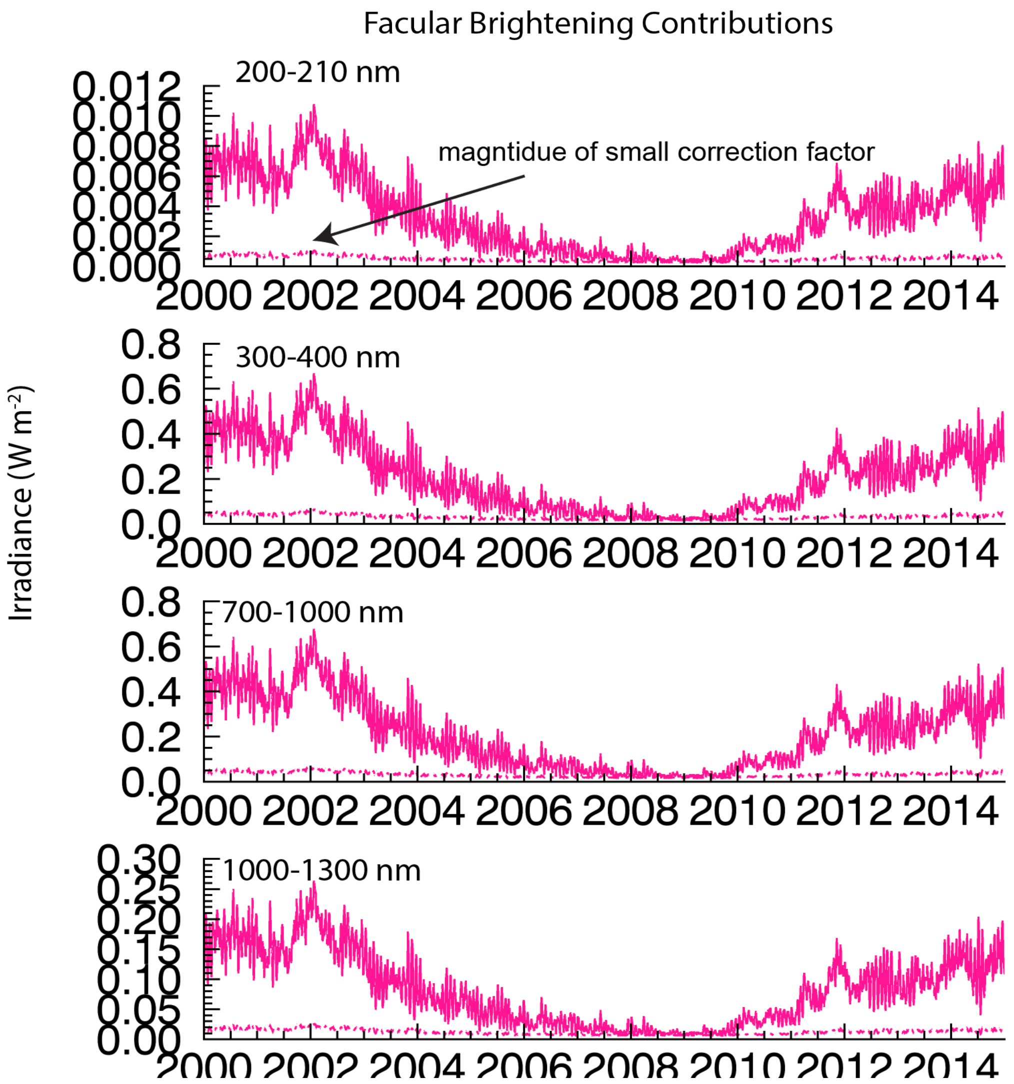
then linearly relating this residual energy to the sunspot darkening index

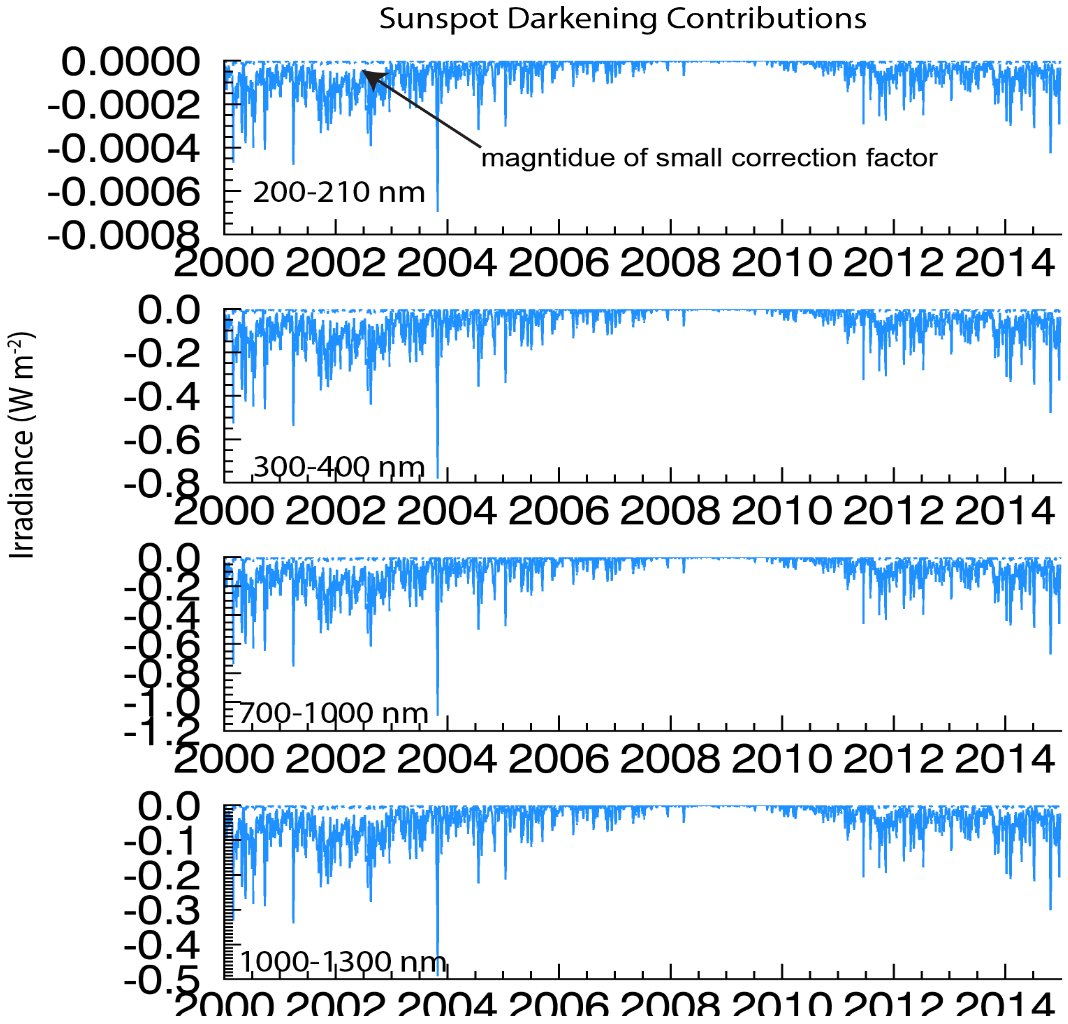
$$R_{spot} = e_S \times [S(t) - S_Q]$$

from which the equivalent increment in the sunspot darkening index is determined as

$$\Delta S(t) = \frac{R_{spot}(t)}{b_S} = \frac{e_S \times [S(t) - S_Q]}{b_S}$$

Magnitude of the “Correction Factor”, $\Delta F(t)$ and $\Delta S(t)$



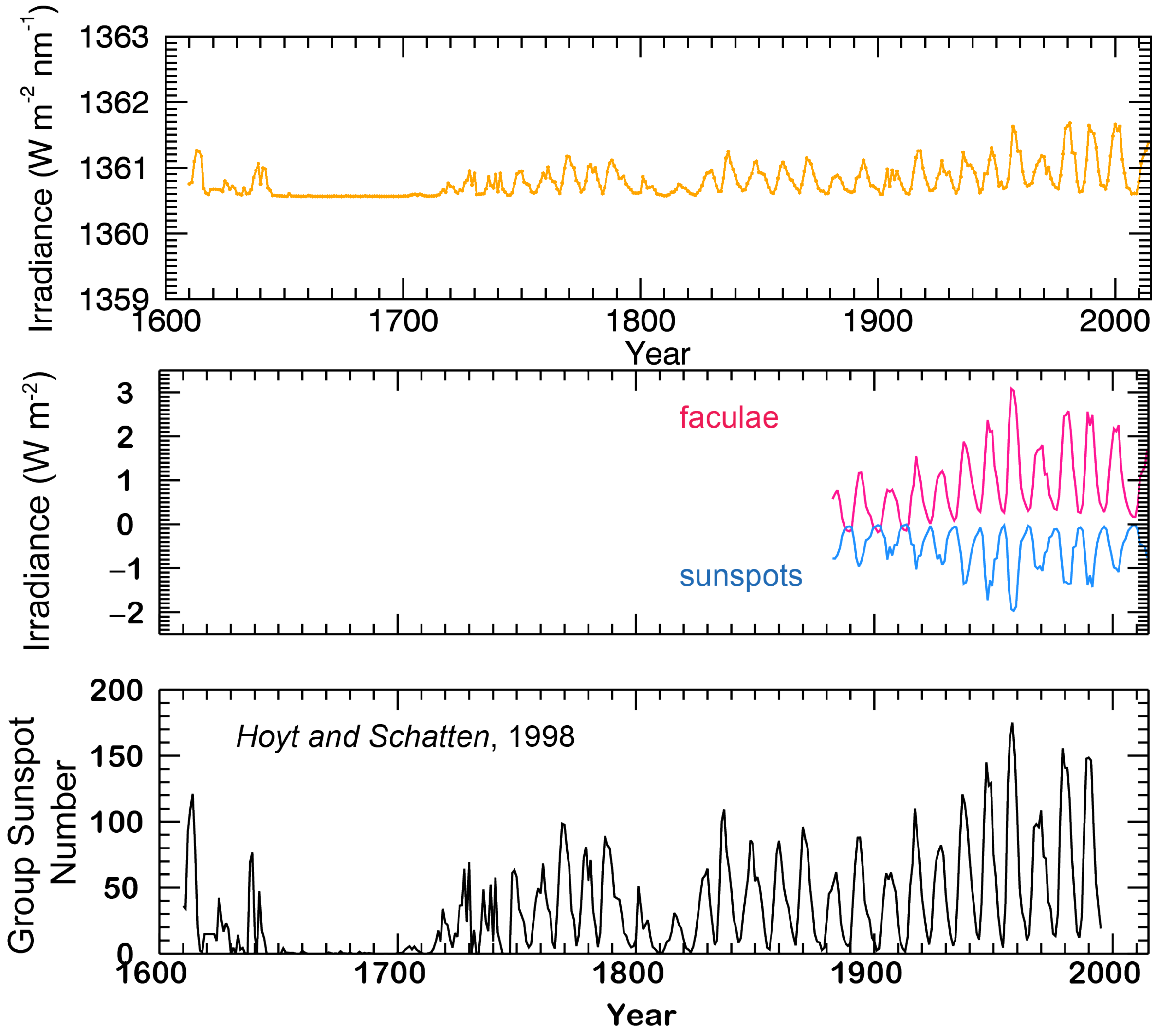


NRLSSI2 Error Estimation: Putting some numbers to it

Quantity	Value and Uncertainty 121.5 nm	Value and Uncertainty 250.5 nm	Value and Uncertainty 500.5 nm	Value and Uncertainty 1000.5 nm
$c_F + c_S$	$(-1\pm7)\times10^{-8}$	$(2\pm3)\times10^{-6}$	$(-1\pm0.9)\times10^{-5}$	$(-9\pm4)\times10^{-6}$
d_F Mg II index scalar	0.0047 ± 0.0001	0.095 ± 0.00001	0.18 ± 0.00002	0.055 ± 0.00002
$F(t)-F_Q$ MgII index change	0.0151 ± 0.003 (20%)	0.0151 ± 0.003 (20%)	0.0151 ± 0.003 (20%)	0.0151 ± 0.003 (20%)
$\Delta F(t)$ MgII index increment	0.0019 ± 0.0004	0.0019 ± 0.0004	0.0019 ± 0.0004	0.0019 ± 0.0004
$\Delta I_F(\lambda, t)$ facular SSI contribution	$(0.8\pm0.2)\times10^{-4}$ W m^{-2} nm^{-1}	$(1.6\pm 0.3)\times10^{-3}$ W m^{-2} nm^{-1}	$(3.0\pm0.6)\times10^{-3}$ W m^{-2} nm^{-1}	$(9.4\pm2)\times10^{-4}$ W m^{-2} nm^{-1}
d_S sunspot index scalar	$(3.68\pm2545)\times10^{-10}$	$(-2.9\pm11)\times10^{-8}$	$(-1.06\pm0.2)\times10^{-6}$	$(-2.05\pm0.3)\times10^{-7}$
$S(t)$ sunspot index change	10647 ± 2129 (20%)	10647 ± 2129 (20%)	10647 ± 2129 (20%)	10647 ± 2129 (20%)
$\Delta S(t)$ sunspot index increment	565 ± 113	565 ± 113	565 ± 113	565 ± 113
$\Delta I_S(\lambda, t)$ sunspot SSI contribution	$(4\pm1)\times10^{-6}$ W m^{-2} nm^{-1}	$(-3.28\pm0.77)\times10^{-4}$ W m^{-2} nm^{-1}	-0.012 ± 0.002 W m^{-2} nm^{-1}	-0.023 ± 0.005 W m^{-2} nm^{-1}
$I(\lambda,t) - I_Q(\lambda)$ SSI change	$(0.83\pm0.18)\times10^{-4}$ W m^{-2} nm^{-1}	0.0013 ± 0.0004 W m^{-2} nm^{-1}	-0.009 ± 0.003 W m^{-2} nm^{-1}	-0.0013 ± 0.0007 W m^{-2} nm^{-1}
$I_Q(\lambda)$	$(1.36\pm0.14)\times10^{-4}$ W m^{-2} nm^{-1} (10%)	0.0548 ± 0.003 W m^{-2} nm^{-1} (5%)	1.909 ± 0.1 W m^{-2} nm^{-1} (5%)	0.7422 ± 0.04 W m^{-2} nm^{-1} (5%)
$I(\lambda,t)$ absolute value	$(2.19\pm0.17)\times10^{-4}$ W m^{-2} nm^{-1}	0.0561 ± 0.0034 W m^{-2} nm^{-1}	1.900 ± 0.103 W m^{-2} nm^{-1}	0.7409 ± 0.0407 W m^{-2} nm^{-1}

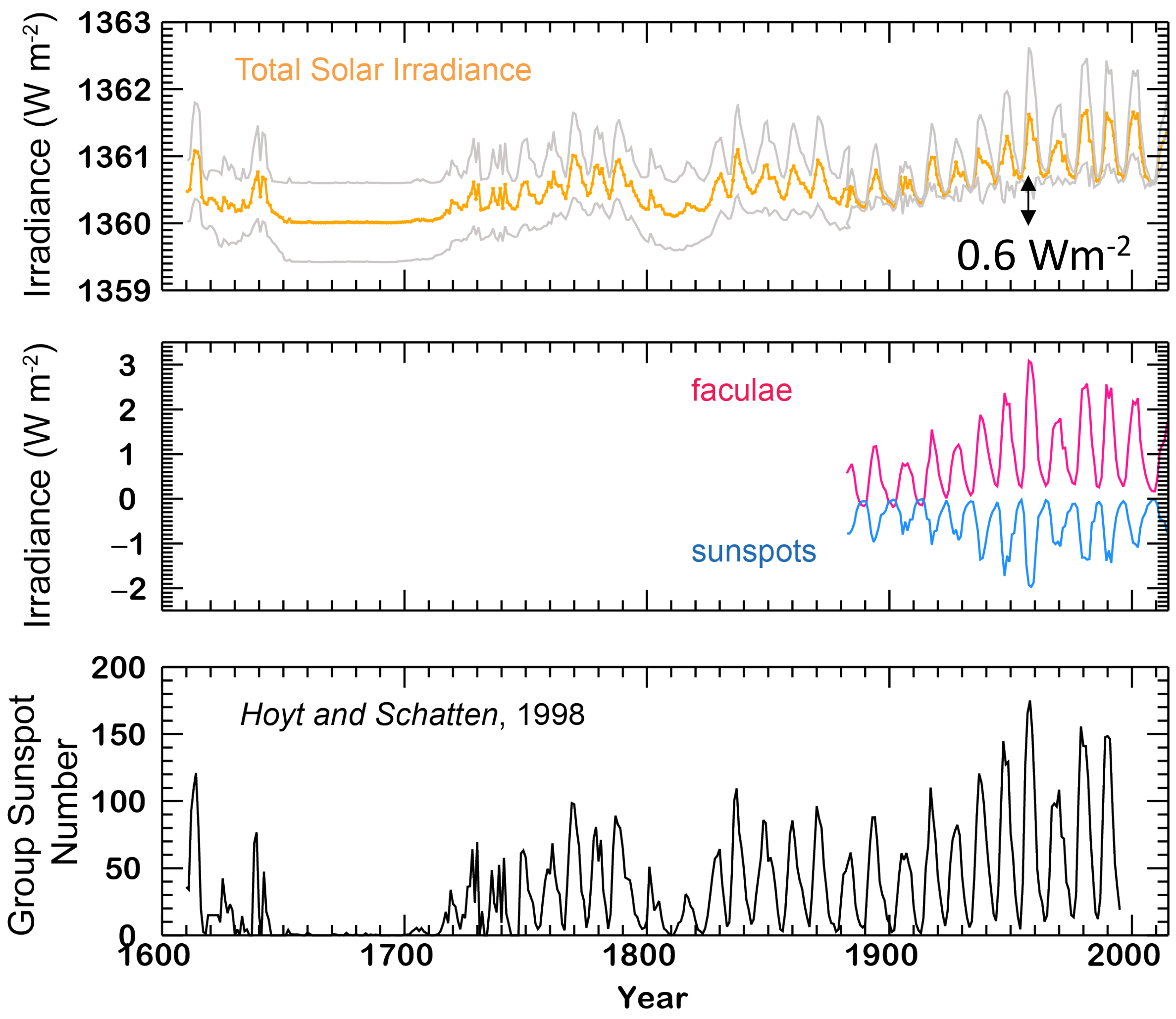
Reconstructing Historical TSI & SSI: “Cycle”

- Lean et al. [2001] detail the various proxy indicators of solar magnetic variability used as inputs to the NRL models.
  - Facular Brightening
    - Mg II index: 1978 onward
    - Ca II K index: 1974 onward
    - He I Index: 1974 onward
    - F10.7-cm flux: 1974 onward
    - Plage index: 1944-1987
    - Visible solar images: prior to 1940
    - Group Sunspot Number: 1610 onward
  - Sunspot Darkening
    - USAF SOON:1982 onward
    - RGO: 1882-1982.
    - Group Sunspot Number: 1610 onward



Reconstructing Historical TSI: "Background"

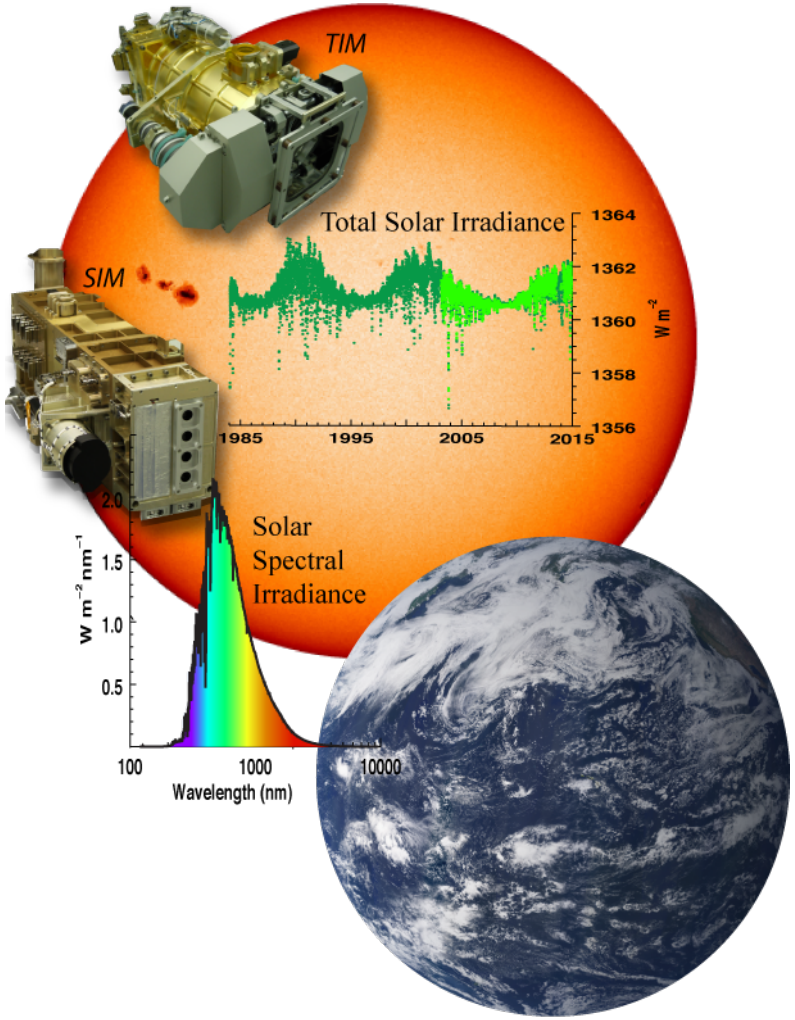
- A long-term secular component in facular brightening is speculative
  - Chromospheric emission in "cycling" stars is higher than in "non-cycling" stars [Baliunas and Jastrow, 1990; Lean et al., 2001; Lean et al., 2005].
  - In NRLTSI2, the increase in Maunder Minimum to present-day quiet Sun is ~ 0.04% (0.6 W m^{-2}).
  - Various estimates exist
    - Lean [2002]: ~ double
    - Wang et.al [2005]: similar
    - Krivova et al. [2010]: similar
    - Shapiro et al. [2011]: order of magnitude larger
    - Judge et al. [2012]: indicate Shapiro et al. [2011] too large by factor or 2
    - Feulner [2011]: < 1 Wm-2, possibly 0 to 0.3 W m-2



Sectoin 2: Operational Implementation

- NRLTSI2 and NRLSSI2 were transitioned in operational capability to the NOAA NCEI Climate Data Record (CDR) program in 2015

Deliverables



Product	Type	No. of wavelength bins	Time range, update cadence
TSI composite	Observational composite	—	1978–2014, periodic
TSI (daily and monthly avg)	NRLTSI2 model output	—	1882–2014, quarterly
TSI (yearly avg)	NRLTSI2 model output	—	1610–2014, yearly
SSI (daily and monthly avg)	NRLSSI2 model output	3,785 (variable width)	1882–2014, quarterly
SSI (yearly avg)	NRLSSI2 model output	3,785 (variable width)	1610–2014, yearly
SSI reference spectra	NRLSSI2 model output	99,884 (1-nm width)	Quiet sun Low, moderate, and high solar activity Maunder Minimum
Facular brightening and sunspot darkening indices	NRLTSI2/NRLSSI2 model input	—	1882–2014, quarterly

Documentation	**Climate-Algorithm Theoretical Basis Document**
Stewardship	i. Yearly Quality Assurance Reports & replacement of preliminary data with final data ii. Model Input Time Series

Data Access

CDR Program: https://www.ncdc.noaa.gov/cdr

LASP LISIRD: http://lasp.colorado.edu/lisird3/data/nrl2_files

Quality Assurance

- Statistical techniques will improve estimates in the modeled SSI
- The model inputs rely ground and space-based observations of sunspot regions and global facular brightness:
  - Accuracy and precision is largely unknown.

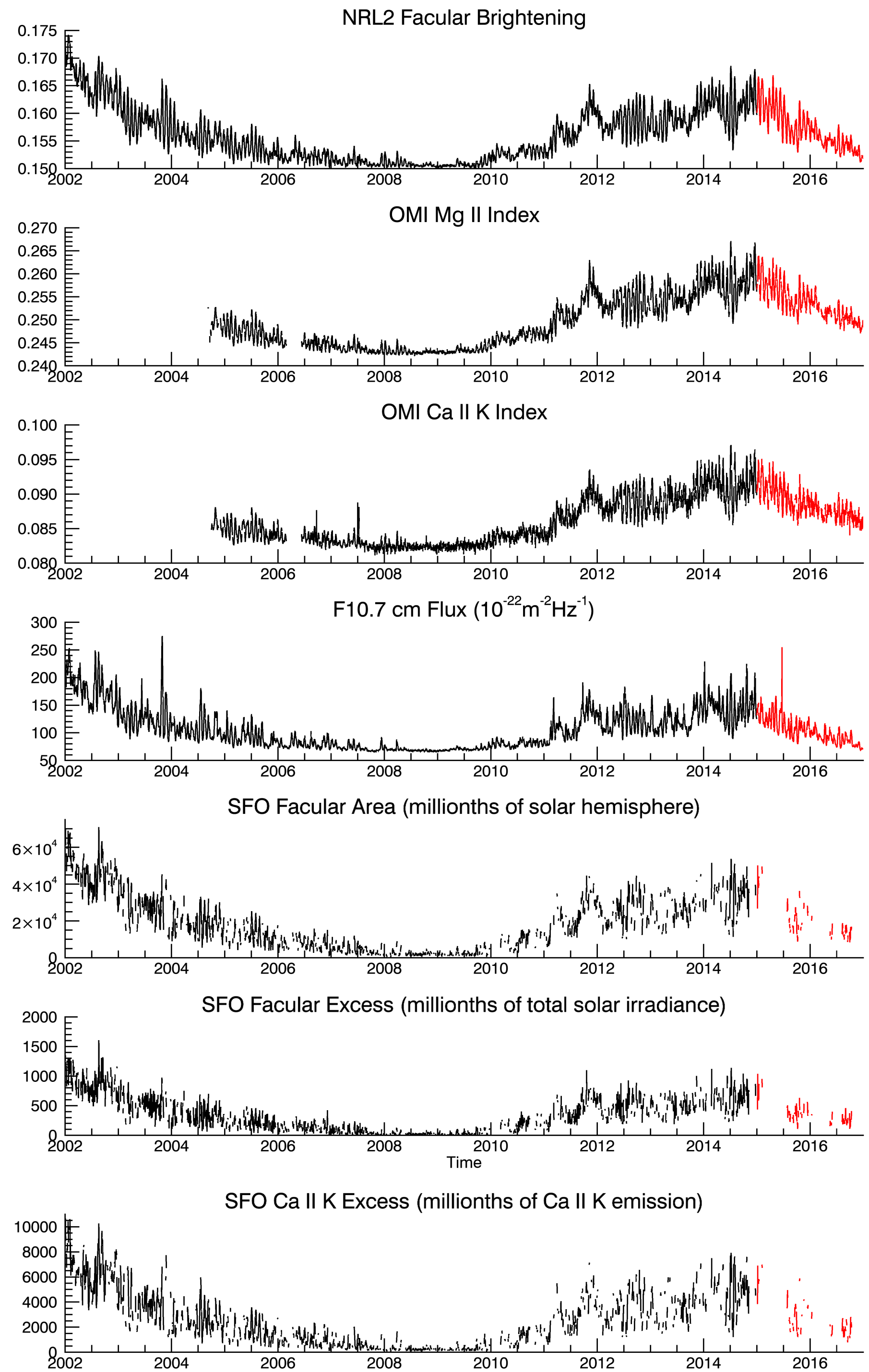
Statistical Quantity	Variable(s)
Correlations	Between modeled and measured (SORCE, TCTE, TSIS) solar irradiance Between sunspot area and sunspot number Between Mg II index and F10.7 cm flux Between USAF SOON sunspot area and Debrecen sunspot area
Means	Sunspot Blocking Function Facular Brightening Function
Standard Deviations	Sunspot Blocking Function Facular Brightening Function Residuals between modeled and measured solar irradiance

Model Inputs	Quality Flags Raised for Questionable or Implausible Values
Sunspot blocking function	Missing Station Data Duplicate Records Larger (or smaller) than expected variability Outliers
Facular brightening function	Time Gaps Larger (or smaller) than expected variability Outliers

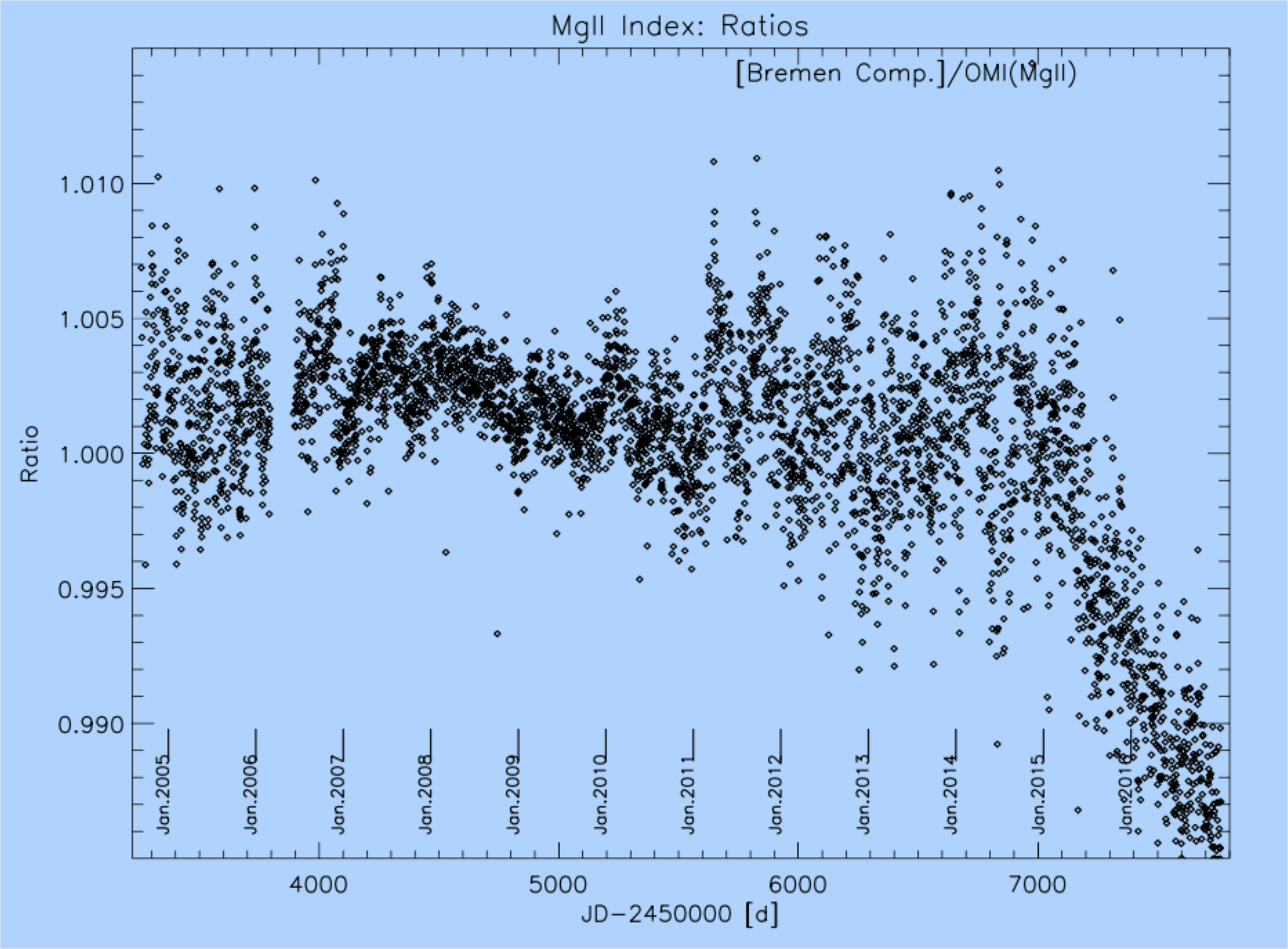
Statistical Comparisons & Correlations: Model Inputs with Other Proxies of Solar Activity

Proxies of Facular Activity

This is only a subset…



Comparison of Univ of Bremen and OMI Mg II

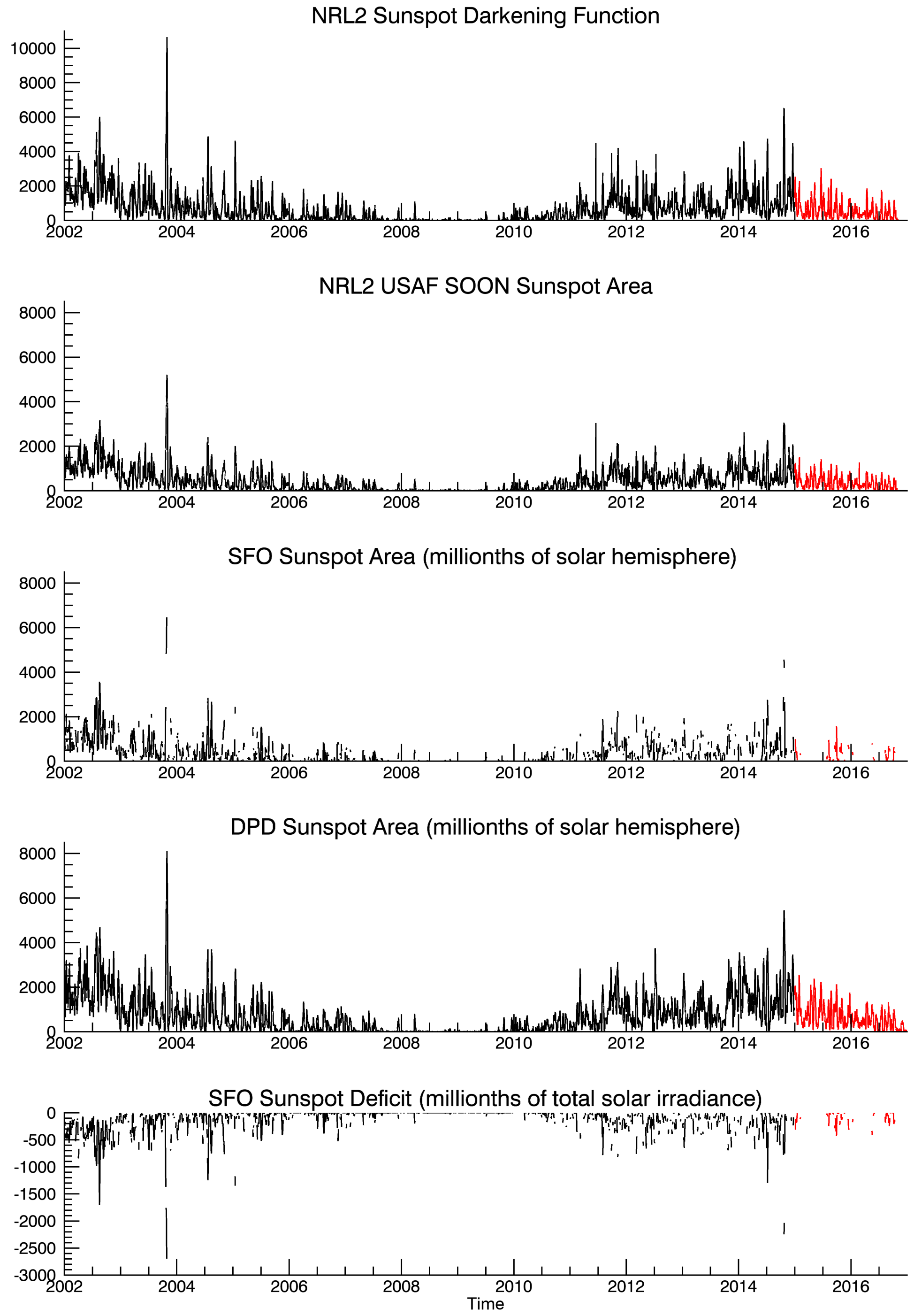


Courtesy Sergey Marchenko and Matt DeLand

Statistical Comparisons & Correlations: Model Inputs with Other Proxies of Solar Activity

Proxies of sunspot darkening

This is only a subset…



Statistical Comparisons & Correlations: Model Inputs with Other Proxies of Solar Activity

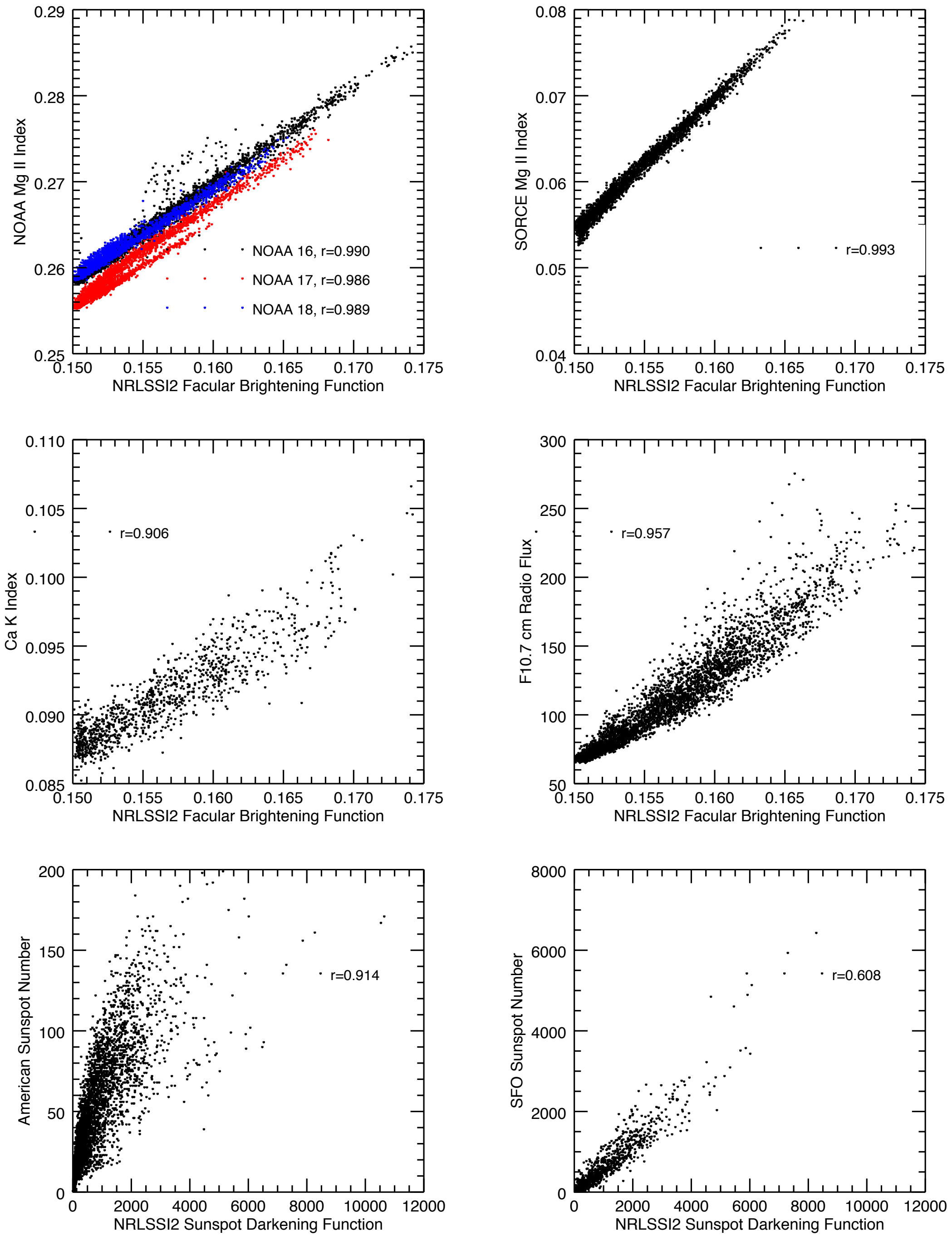
Monitoring correlations over time can be used as an indicator of change,

Correlation between NRL2 sunspot blocking function and USAF SOON sunspot area:

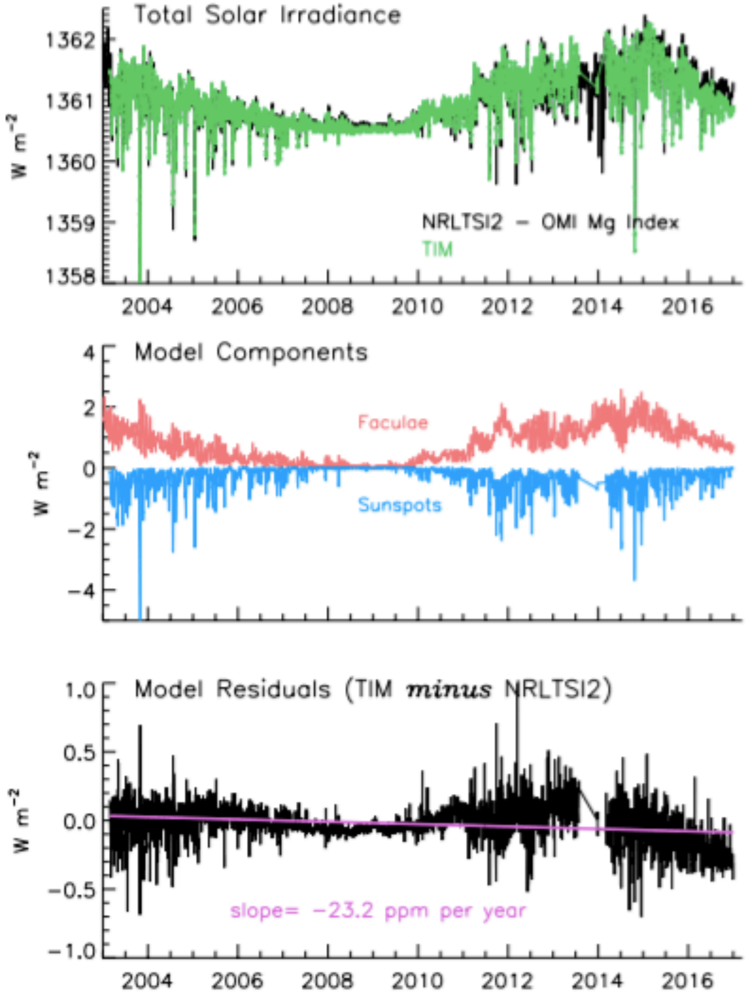
2001-2014 = 0.9554

2001-2016 = 0.9546

but how to translate this to an uncertainty that can quantify model assumptions?

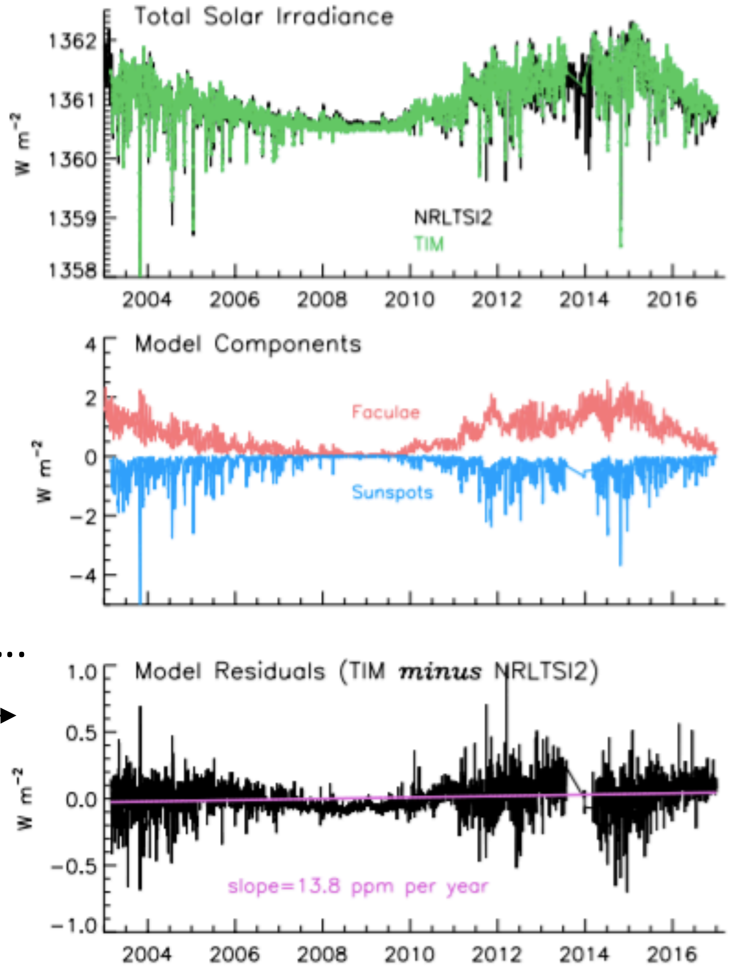


NRLTSI model with different facular brightening inputs.



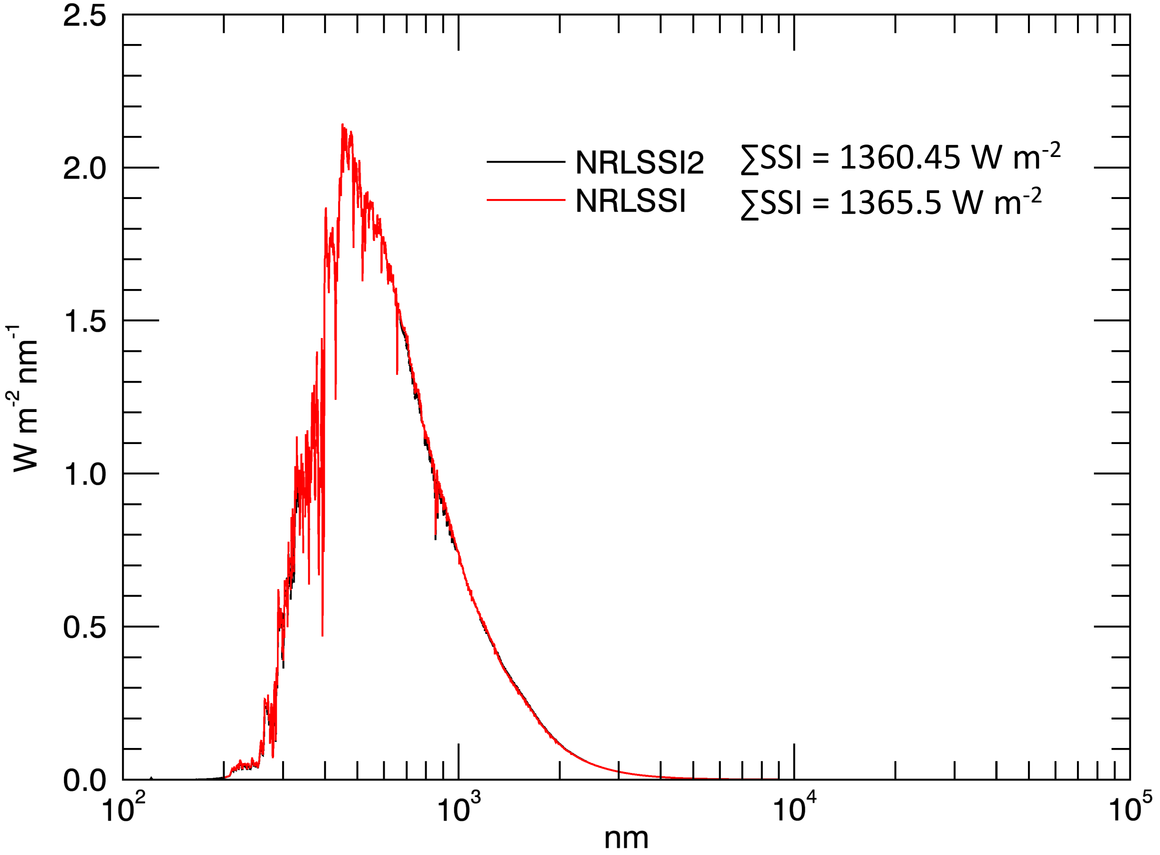
Using OMI Mg II Index….

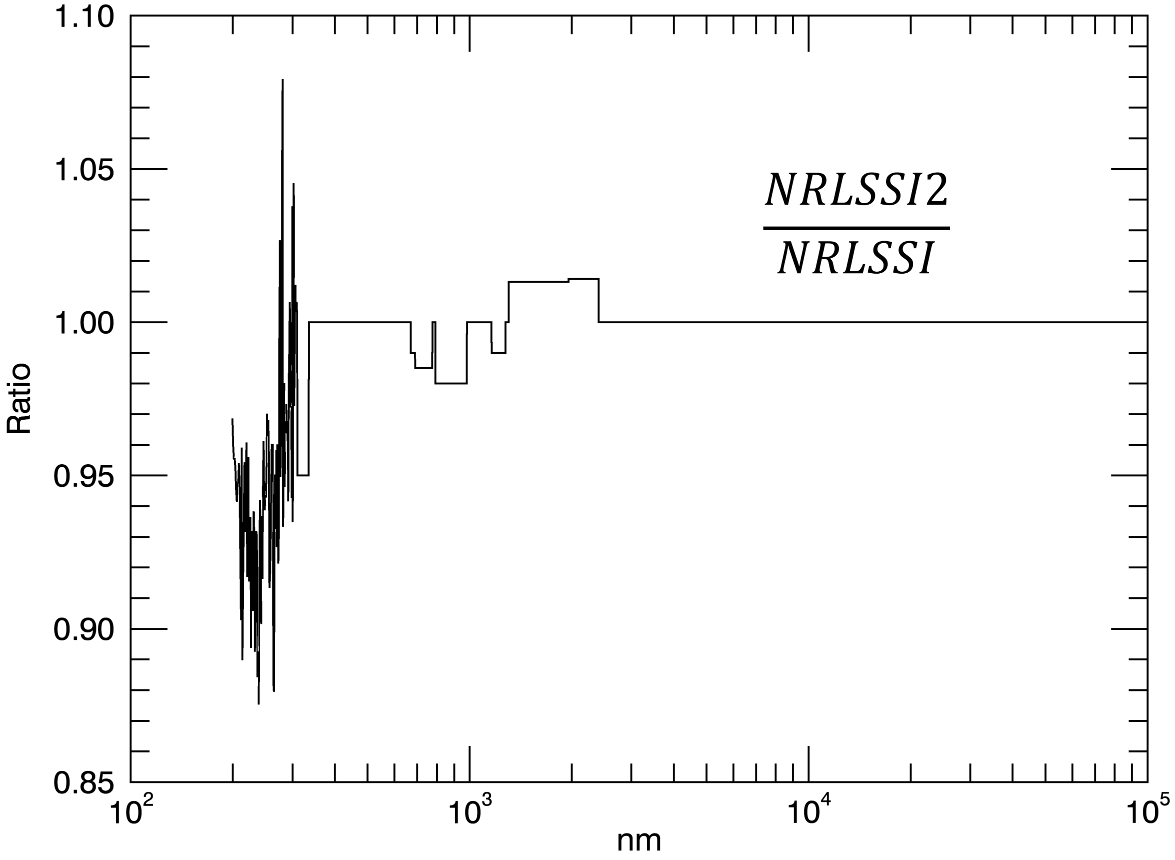
Using Univ. of Bremen Mg II Index….



Section 3: Comparisons to Original NRL model

Comparison of Quiet sun reference in the original and updated (v2) NRL model

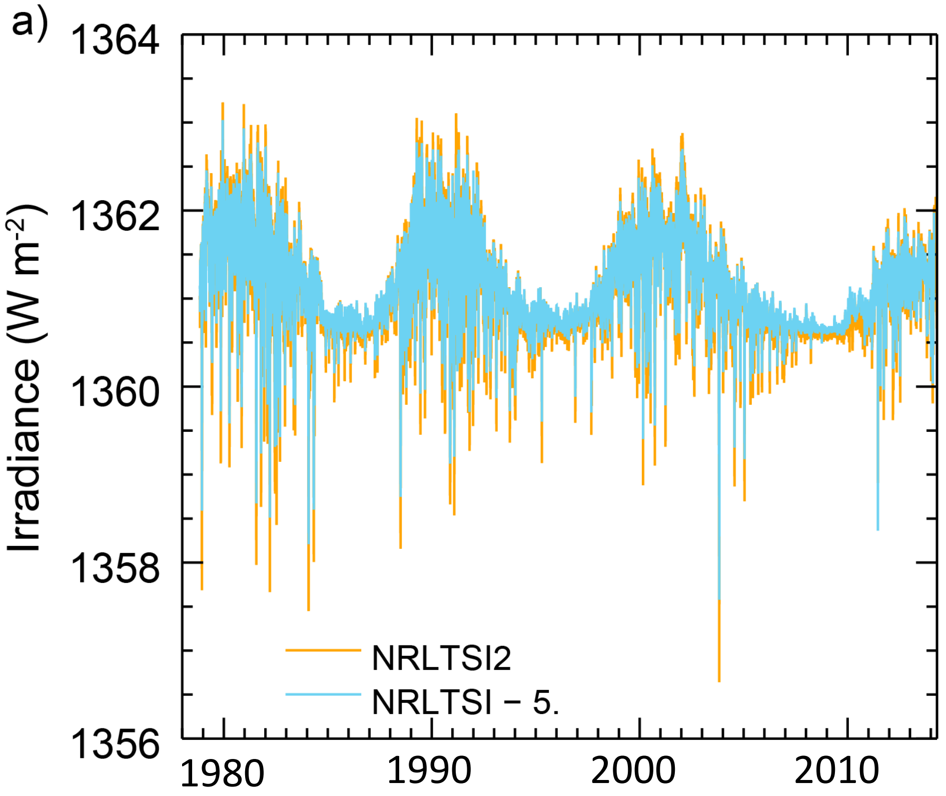


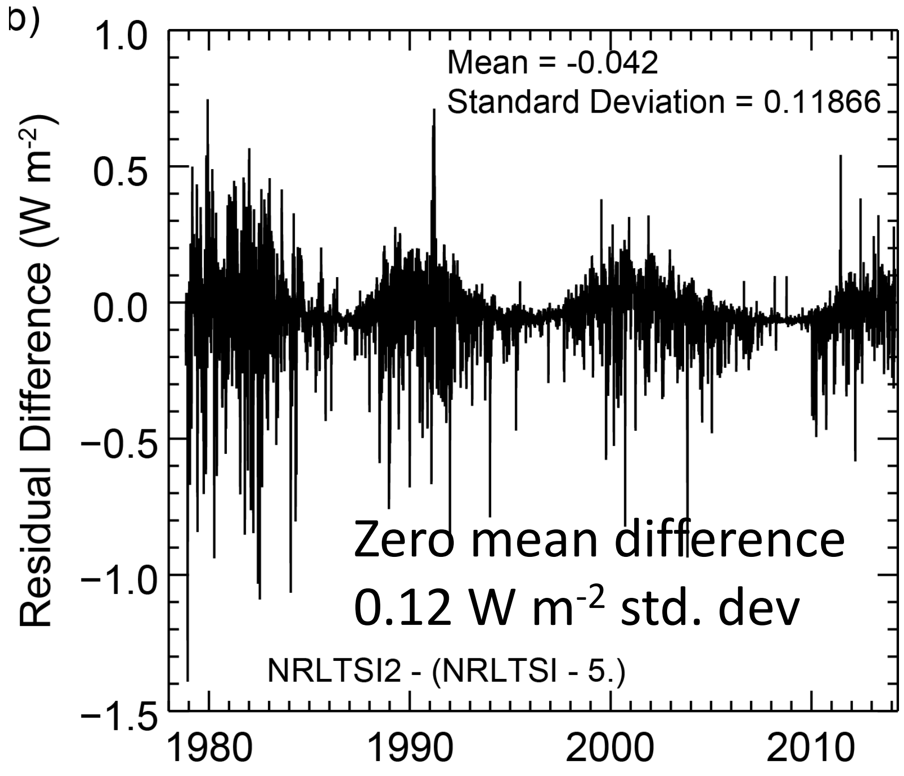


Original NRLSSI reference spectrum: An average of SOLSTICE observations during the UARS era (between 120 and 400 nm) and SOLSPEC (ATLAS-1) observations between 401-874 nm. Kurucz (1991) model was used for wavelengths > 874 nm.

Differences in NRLTSI2 and original NRLTSI. ***(Error estimates*** are new to NRL, Version 2.)

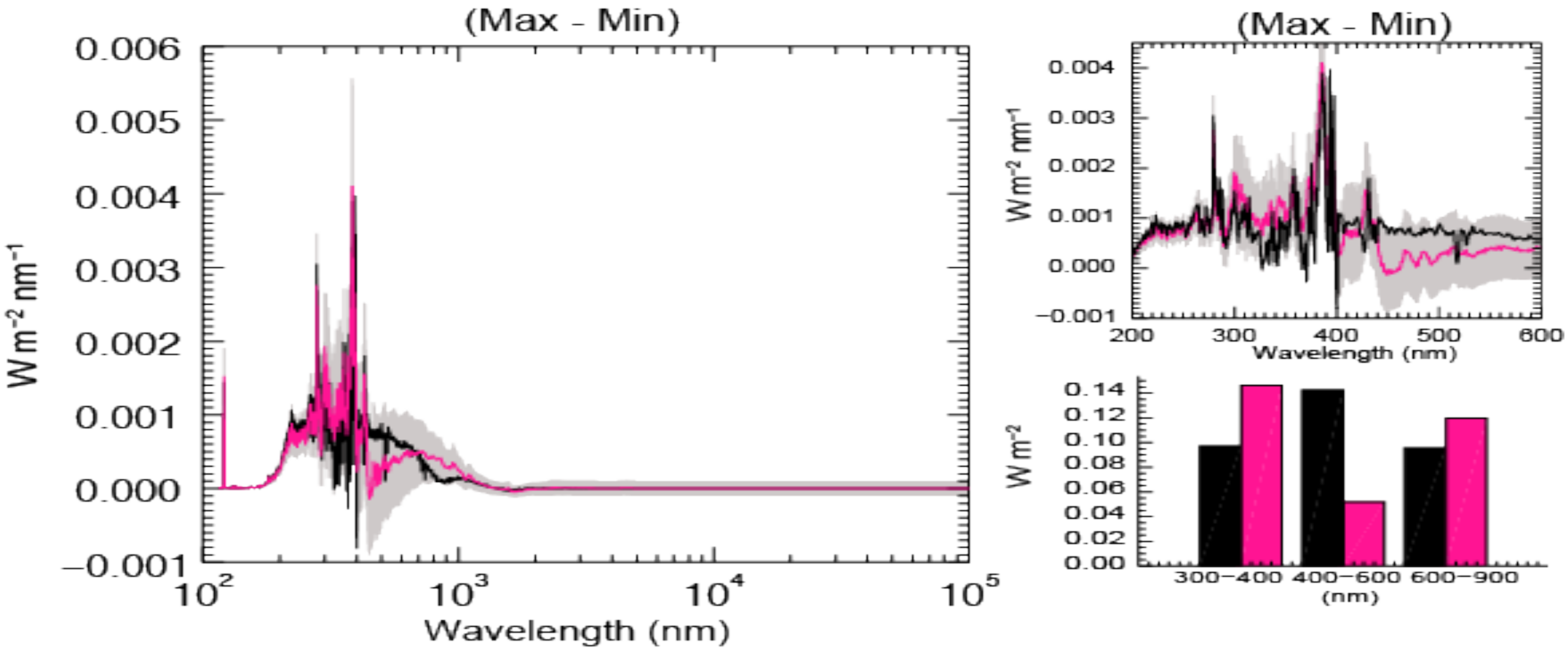
Model Inputs	NRLTSI	NRLTSI2
Quiet sun reference	1365.5 W m-2	1360.45 W m-2
Measurement record	Composite TSI record: 1978-2003 [Frohlich and Lean, 2004]	SORCE TIM TSI measurements: 2003-2014
Proxy Input record	[Hoyt and Eddy, 1982] sunspot area record [Viereck et al., 2003] Mg II composite extended with SORCE	[Hoyt and Eddy, 1982] sunspot area record Univ. of Bremen Mg II index composite





Differences in NRLSSI2 and original NRLSSI.

Solar cycle (24) SSI Energy Change



300-400 nm Variability: NRLSSI2 > NRLSSI

400-600 nm Variability: NRLSSI2 < NRLSSI

Section 4: Incorporating science research into new revisions of the solar irradiance CDR

What's new for v02r01? (to be released early 2017).

1. **Improved representation of sunspot darkening index.**
   - **Goal: reduce std. dev of residual differences w.r.t. observations**
2. **Addressing sensitivities in modeled irradiance due to proxy input records.**
   - **Goal: Improve representation of estimated irradiances.**
   - **Impact: Affects relative weighting of sunspots and faculae <u>prior to 1980</u>.**
3. **Addressing impact of revised sunspot number on historical irradiance.**
   - **Goal: Provide 2, independent historical (1610-1882) irradiance time series based on Hoyt and Schatten [1998] and updated SILSO sunspot number records [Clette et al. 2015].**
4. **Improve the Observational TSI CDR composite with additional data.**
   - **Goal: Include RMIB composite, in addition to ACRIM and PMOD composites.**

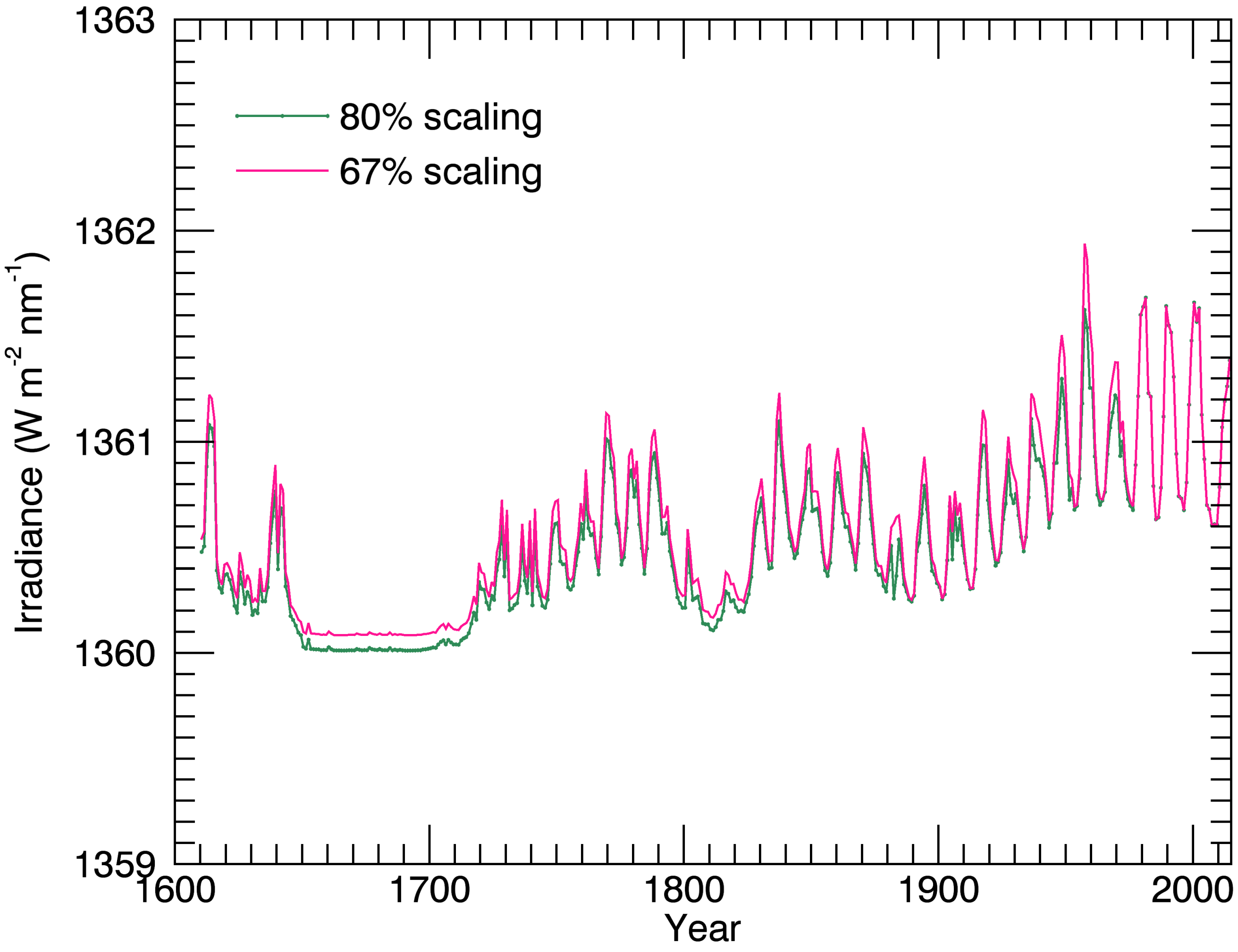
Impacts of Sunspot Area Scaling on Historical TSI

- How do sunspot areas observed by different observatories relate?
- Sunspot Area and Location records:
  - USAF SOON:1982 onward
  - RGO: 1882-1982.

Magnitude of scaling affects the relative roles of sunspots and faculae

Foukal (2014) – 1.2
Fligge and Solanki (1997) – 1.25
Hathaway (2010) – 1.48
Balmaceda et al. (2009) – 1.49

- Willis et al. (2013) – summary of errors in RGO; future paper will provide corrected record.



See Kopp et al., 2016 for further details.

Impacts of Sunspot Area Scaling on Historical SSI

CMIP6 uses preliminary v02r01 data.
V02r01 differs from v02r00 prior to ~ 1978.