How Does the Sun's Spectrum Vary?

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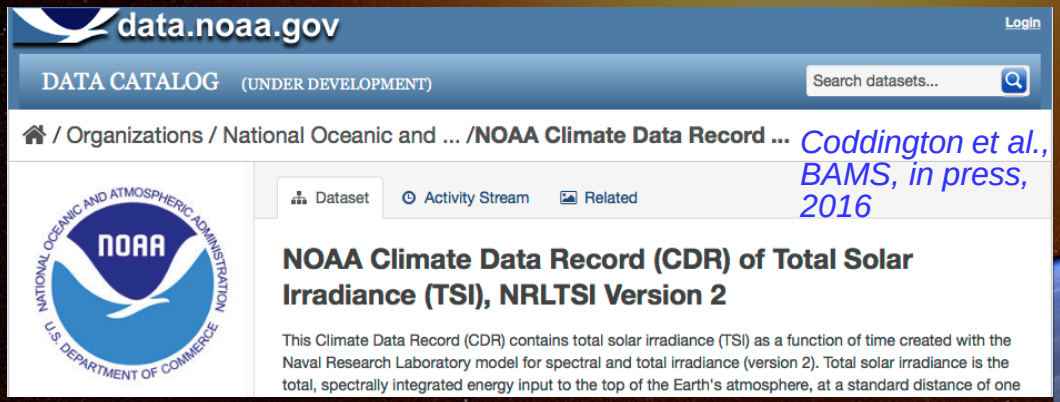
- Solar Rotation – days to months
- Solar Cycle – years to decades
- Long Term – multiple decades

Increasing amplitude
Increasing uncertainty
Decreasing sample size



Coddington et al., BAMS, in press, 2016

Funded by NASA

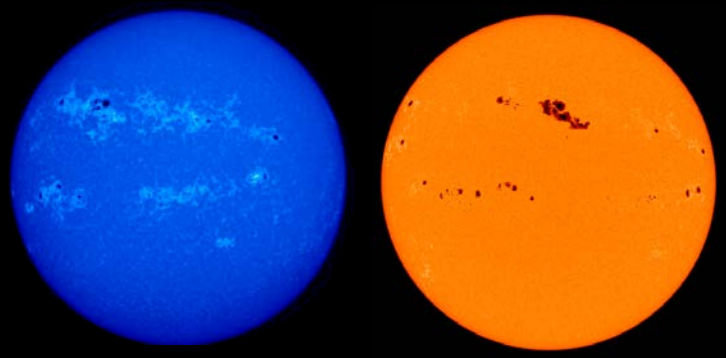
Sunspots and Faculae are (the) Primary Sources of Solar Irradiance Variability

solar spectral irradiance
wavelength
time

solar spectral irradiance of the "quiet" sun… no (solar cycle) magnetic activity

$$F(\lambda,t) = F_{quiet}(\lambda) + \Delta F_{faculae}(\lambda,t) + \Delta F_{spot}(\lambda,t)$$

increase in solar spectral irradiance from bright faculae



decrease in solar spectral irradiance from dark sunspots

$$\int F(\lambda,t)d\lambda \quad \int F_{quiet}(\lambda)d\lambda \quad \int \Delta F_{faculae}(\lambda,t)d\lambda \quad \int \Delta F_{spot}(\lambda,t)d\lambda$$

$$TSI(t) = TSI_{quiet} + \Delta TSI_{faculae}(t) + \Delta TSI_{spot}(t)$$

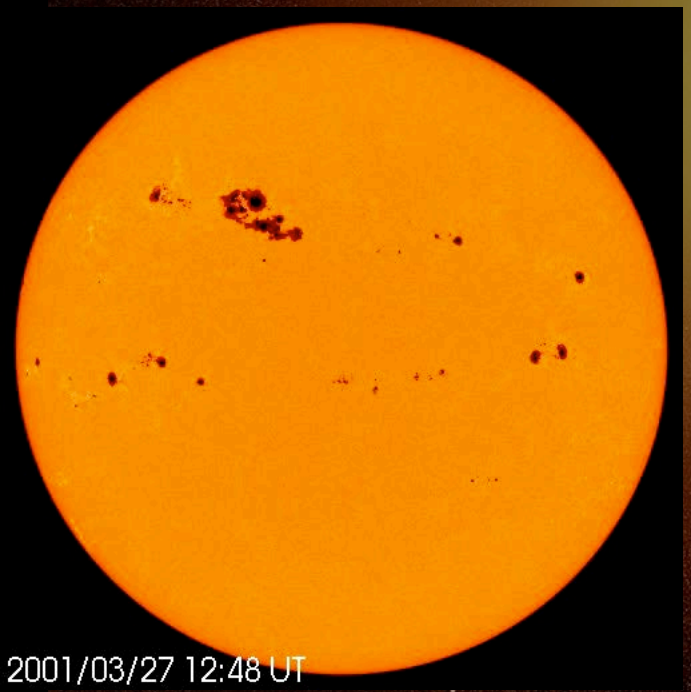
How Does the Sun's Spectrum Vary?

- Solar Rotation – days to months

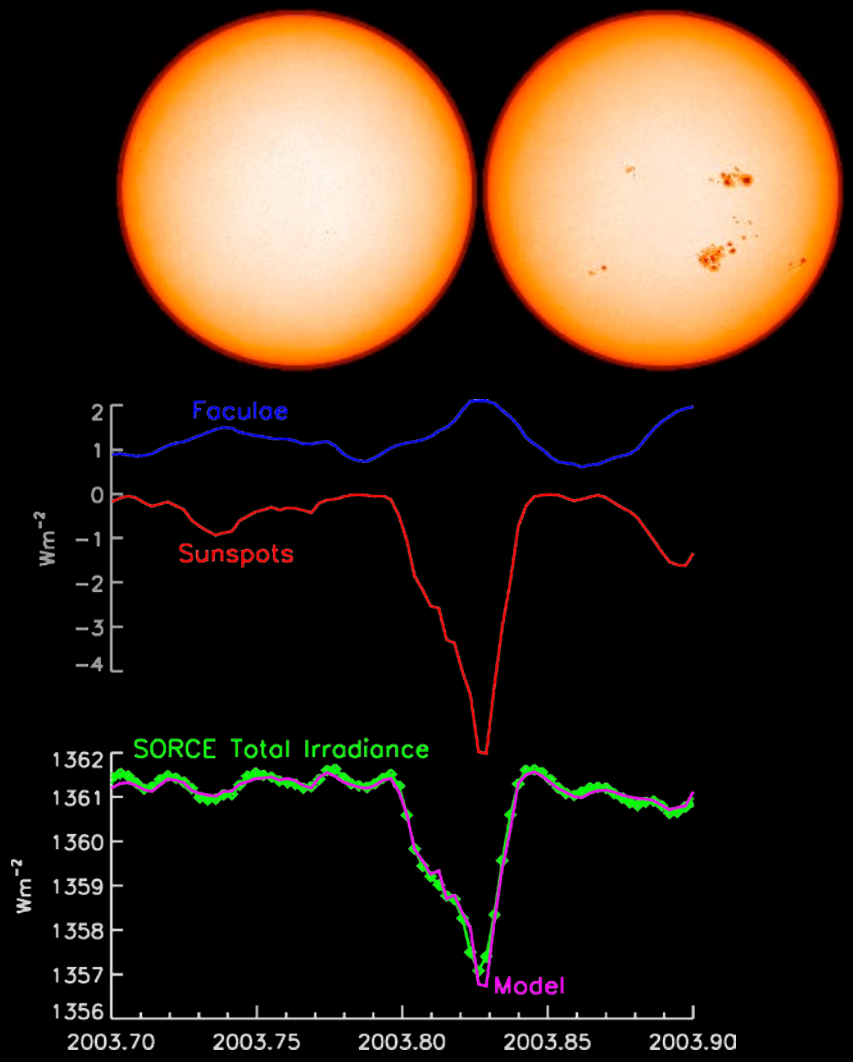
- how well do sunspot and facular indices reproduce observed solar rotational modulation? ….VERY WELL

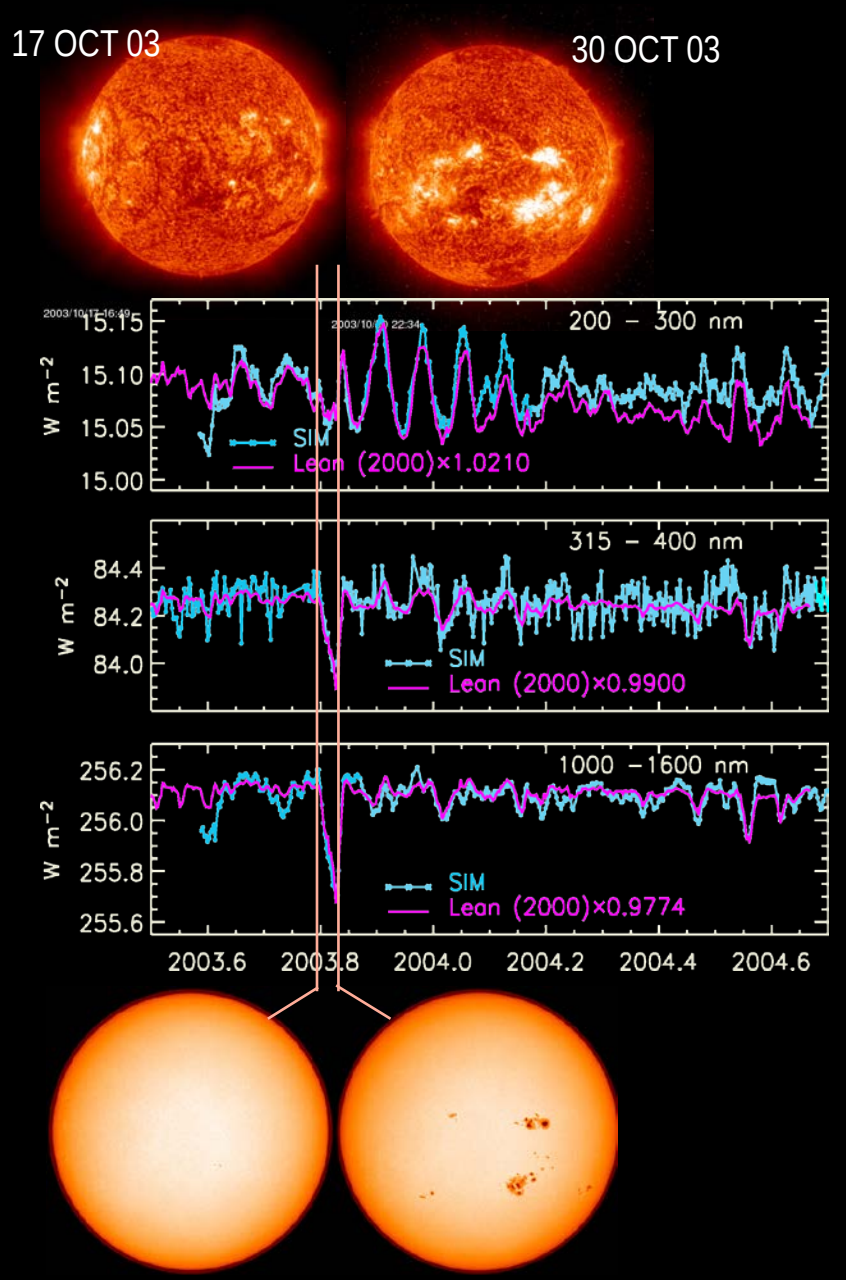
- is solar rotation modulation by sunspots and faculae consistent among independent observations over the past three decades? …. YES

- does bolometric facular variability track UV spectrum variability? … YES



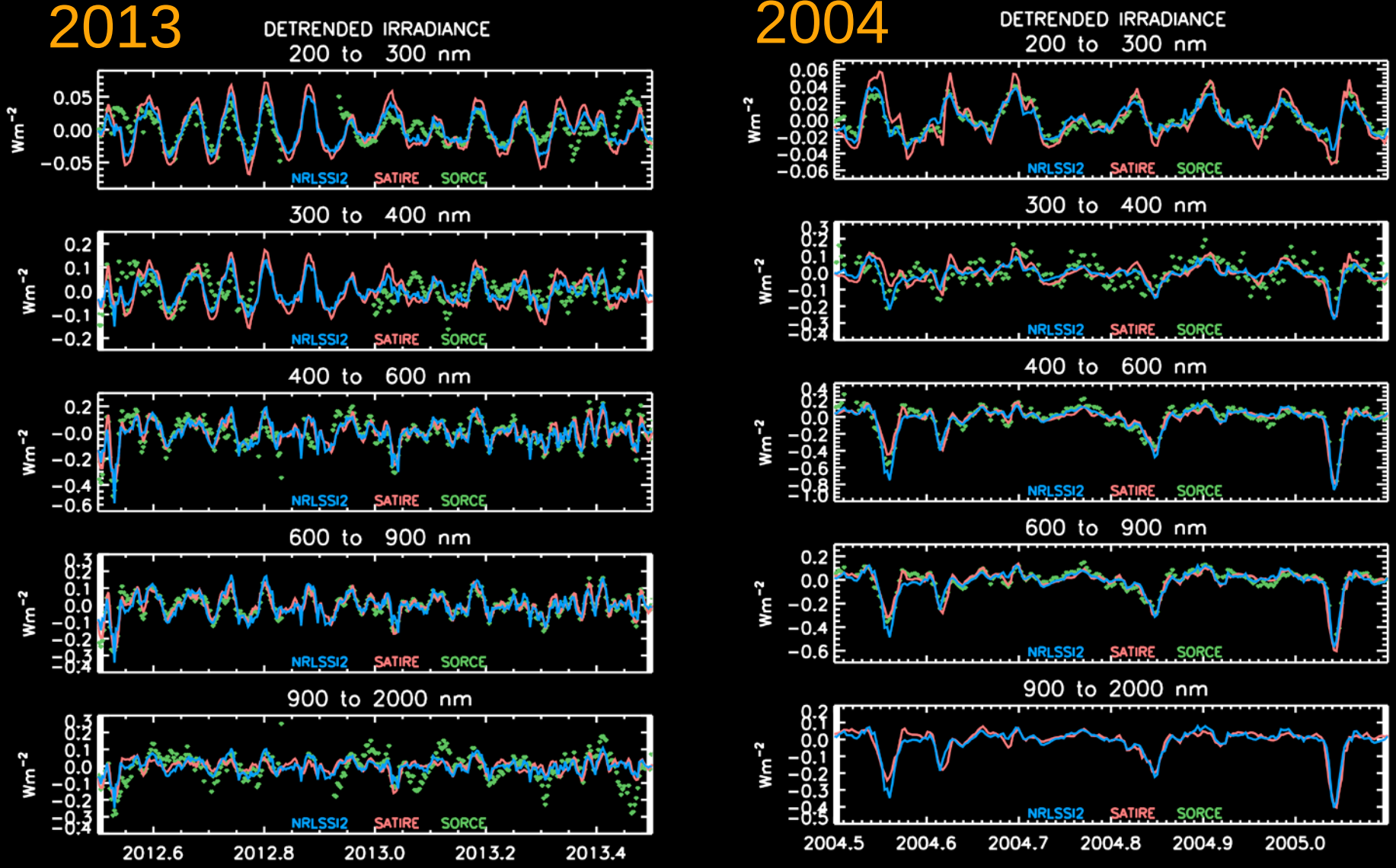
Case Study: October 2003





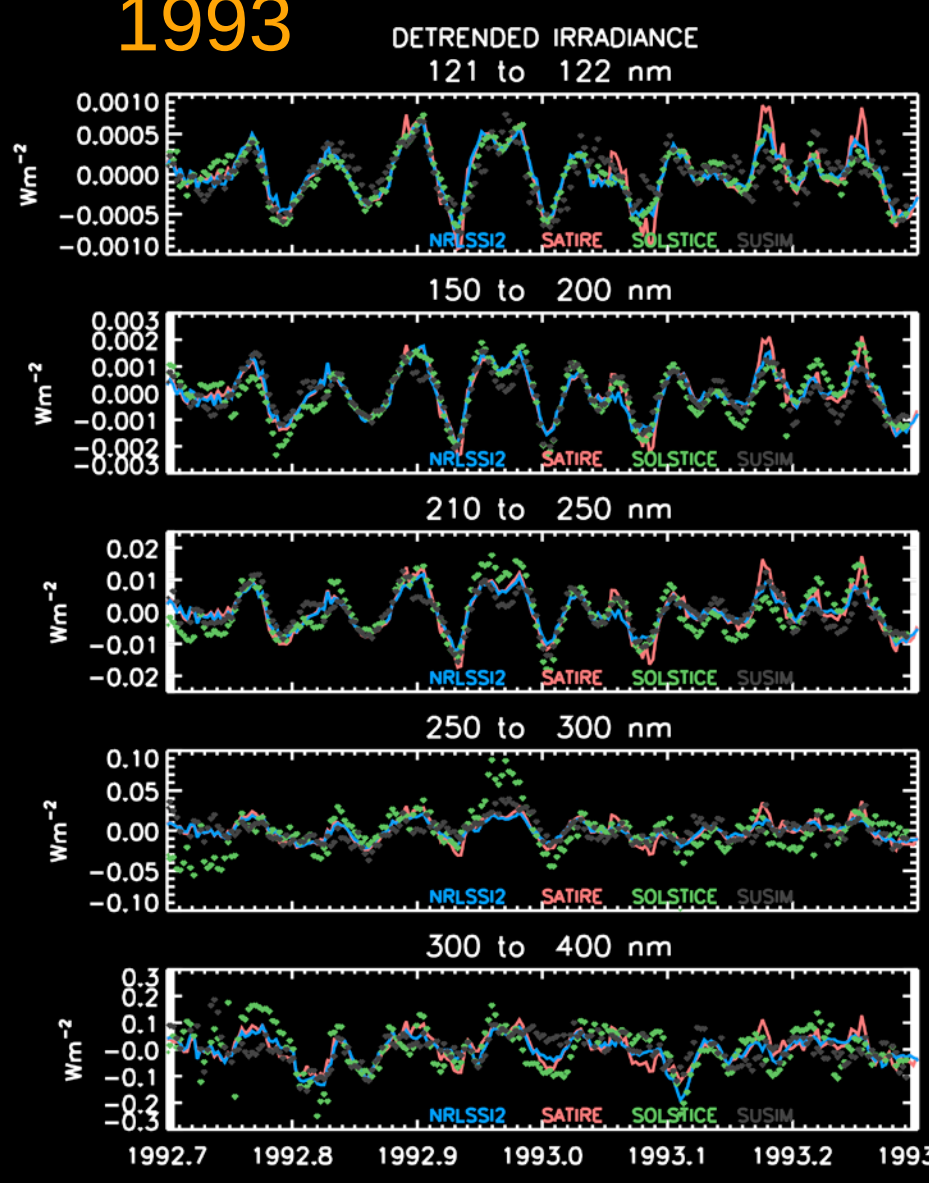
Lean et al., Solar Phys.. 2005

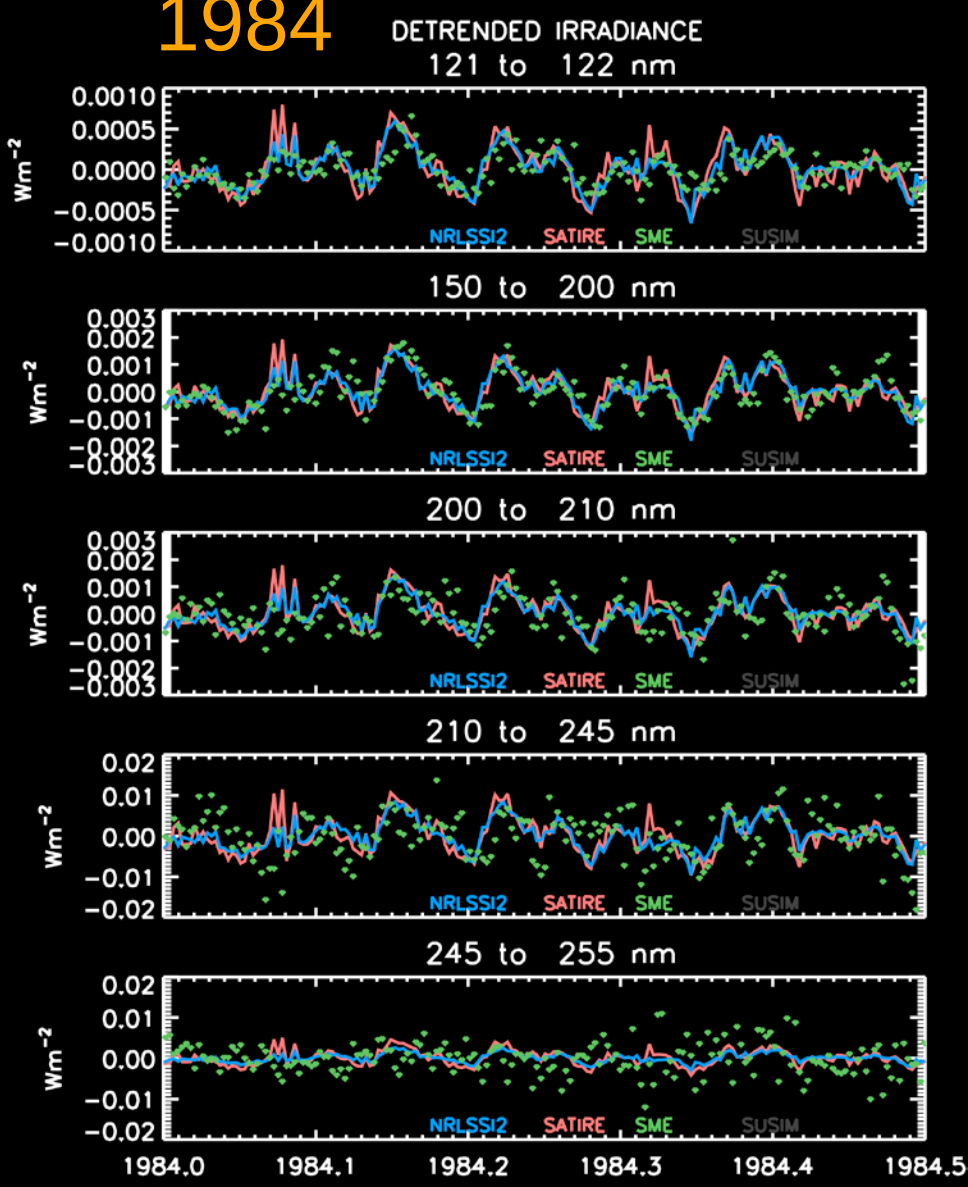
Multipe Solar Rotations: SORCE era



NRLSSI2 model is NOAA CDR, Coddington et al., BAMS, in press, 2016
Marchenko, DeLand and Lean, Space Weather and Space Climate, submitted, 2016

Multipe Solar Rotations: UARS & SME eras





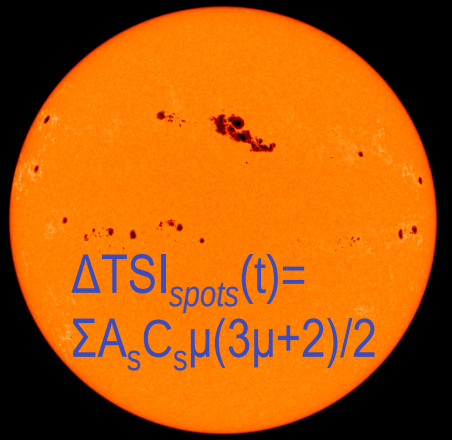
Bolometric Facular vs. UV Spectrum Variability

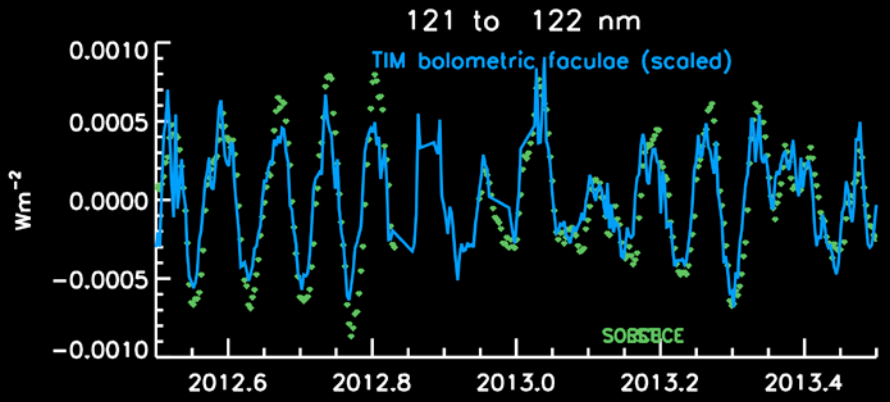
Bolometric facular variability:

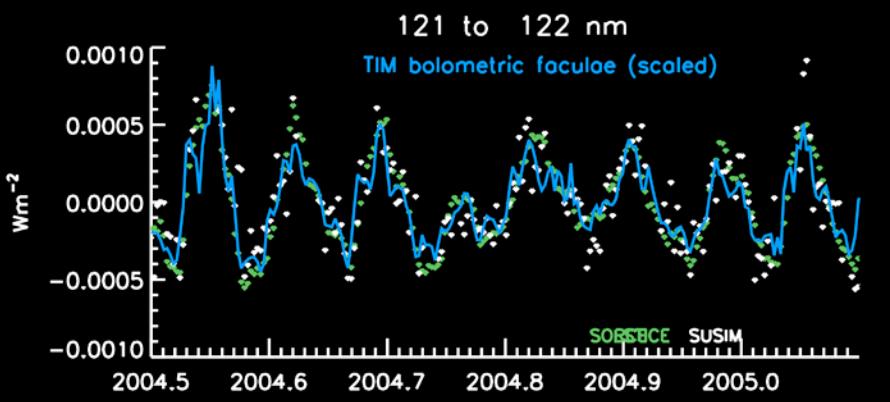
$$\Delta TSI_{faculae}(t) = TSI(t) - \Delta TSI_{spot}(t) - TSI_{quiet}$$

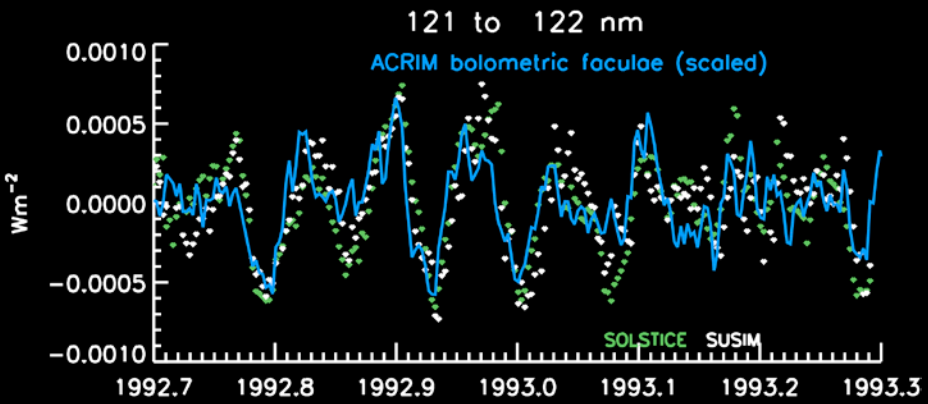
UV spectrum variability, λ <300 nm:

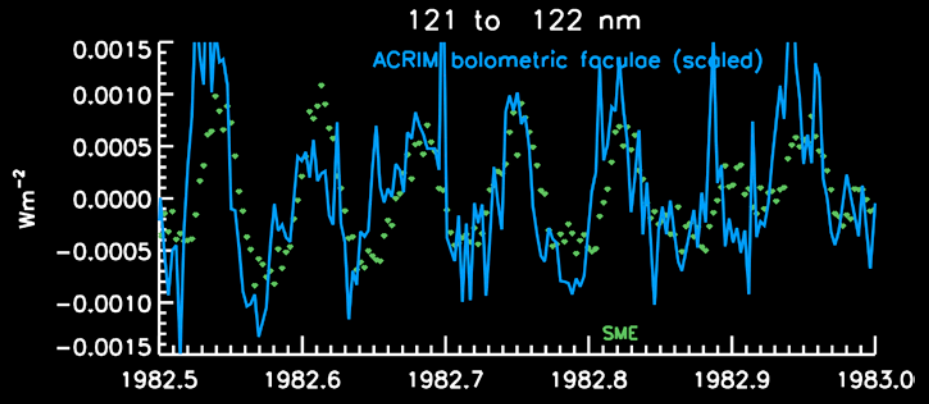
$$\Delta F(\lambda,t) \simeq \Delta F_{faculae}(\lambda,t) \quad (\Delta F_{spot}(\lambda,t) \simeq 0)$$





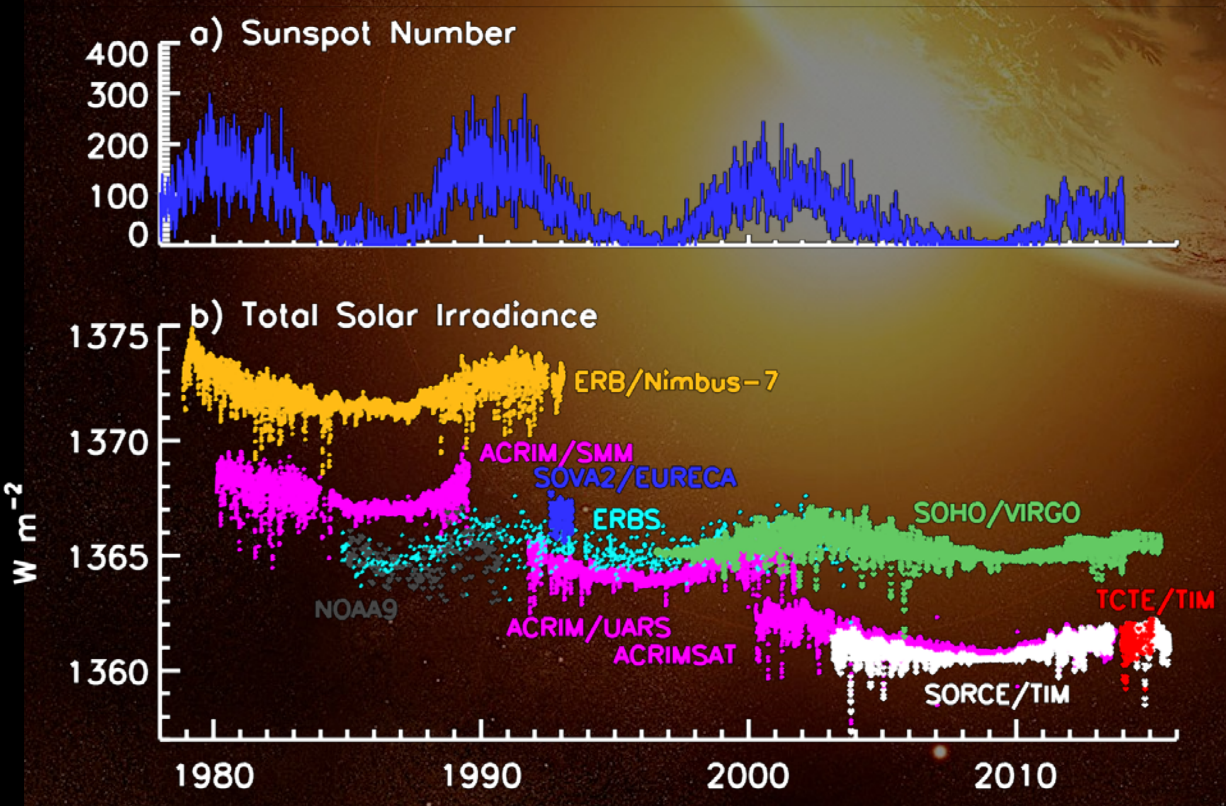






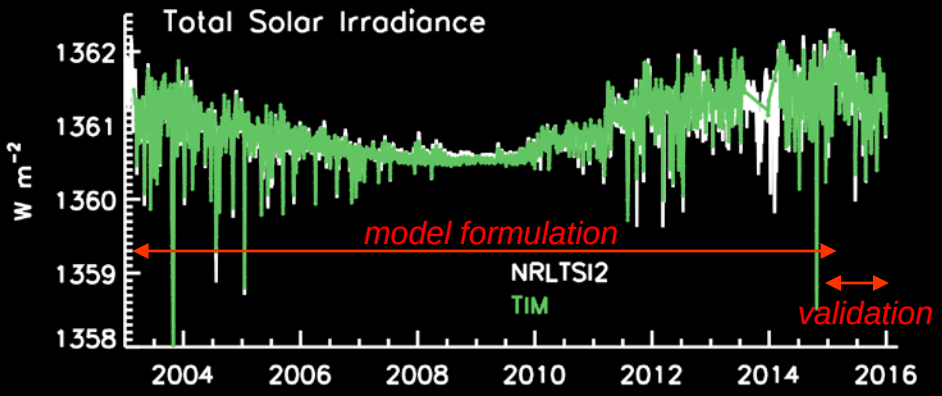
How Does the Sun's Spectrum Vary?

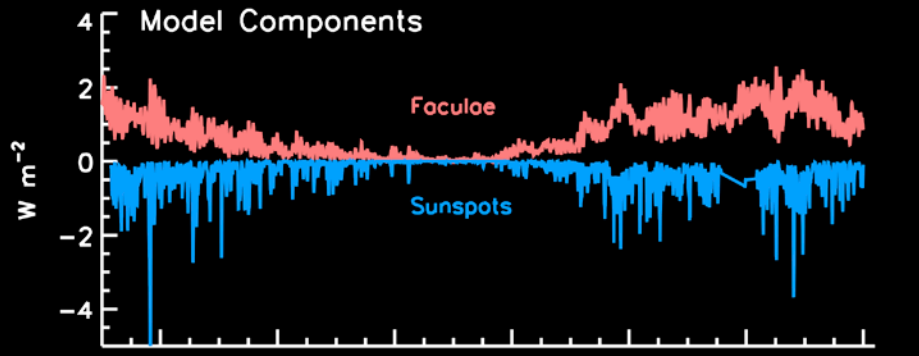
- Solar Cycle – years to decades
  - *- relatively well specified in TSI; poorly specified in SSI*
  - *- how well do sunspot and facular indices reproduce observed TSI cycles?*
  - *- does "adjusted" total solar irradiance (bolometric faculae) track UV cycles?*
  - *- what is the solar cycle change in total minus UV irradiance?*
  - *- reanalysis of existing SME observations for independent validation*

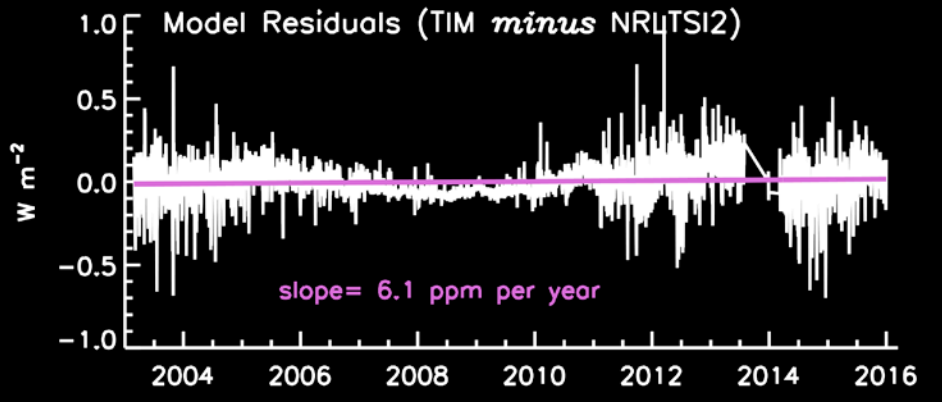


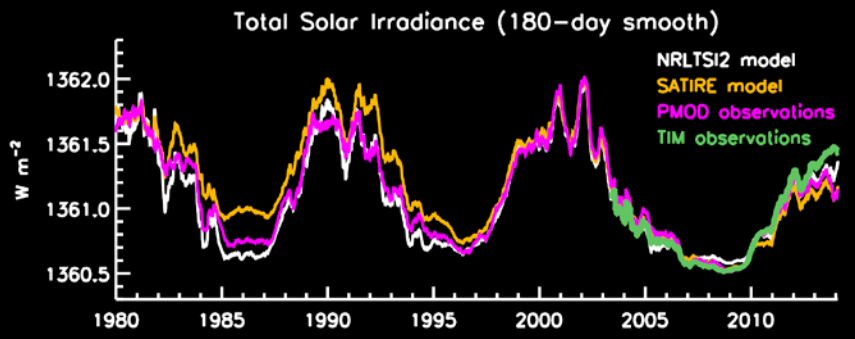
Kopp & Lean, GRL, 2011 (updated)

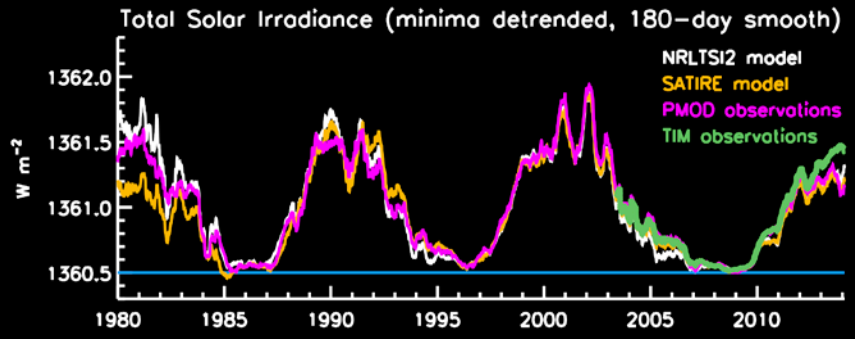
TIM Solar Cycle Observations





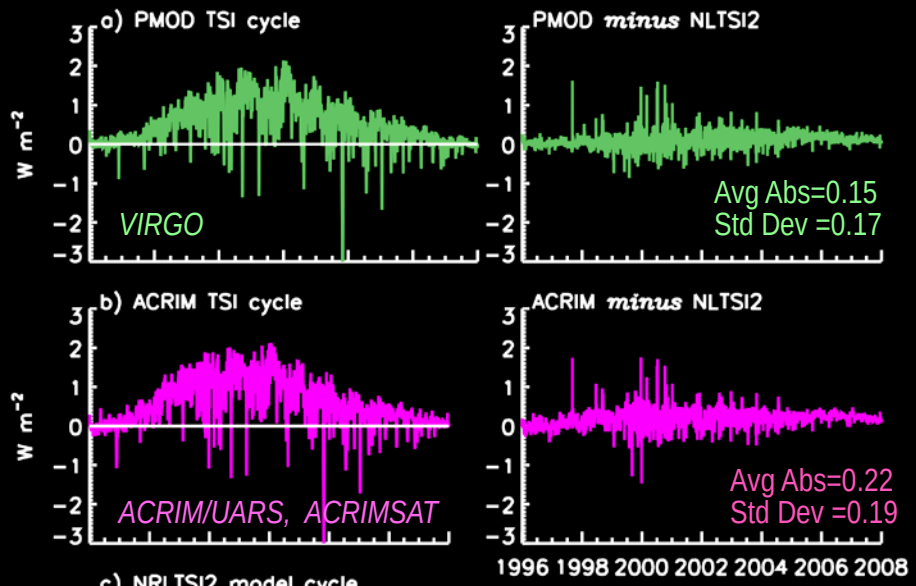




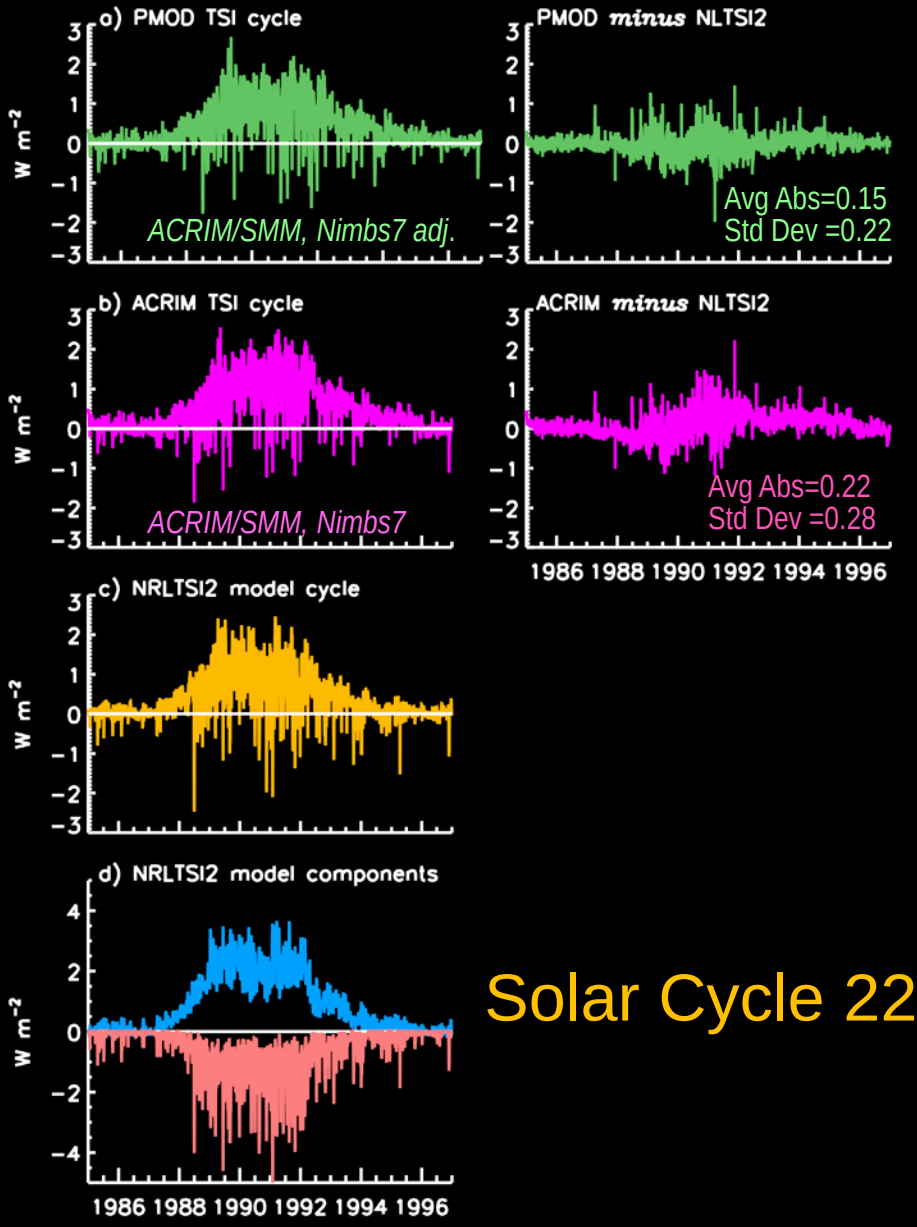


NRLTSI2 reproduces solar cycle changes observed by TIM to within TIM's long-term repeatability of 10 ppm per year.

PMOD & ACRIM Solar Cycle Observations



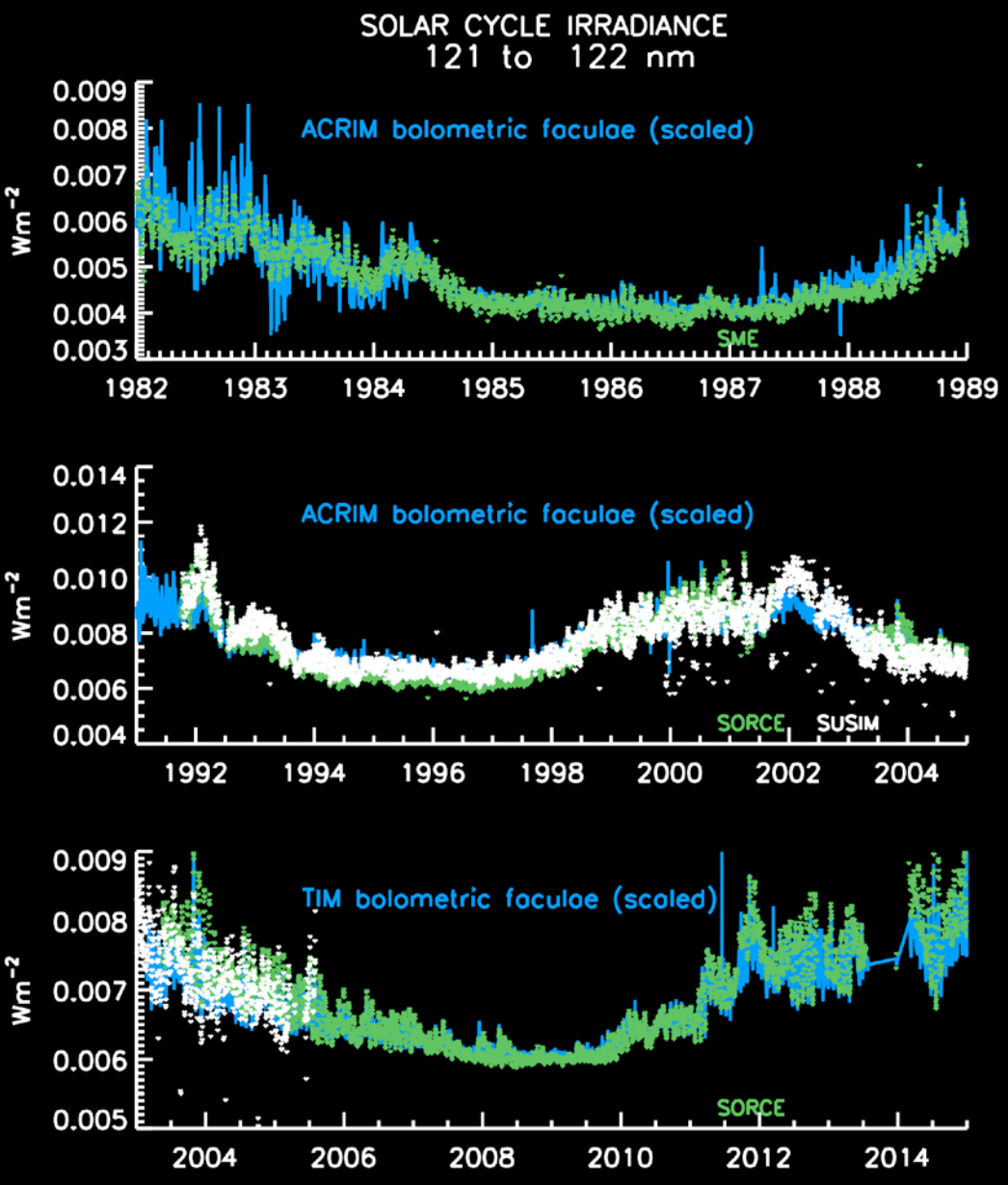
Solar Cycle 23



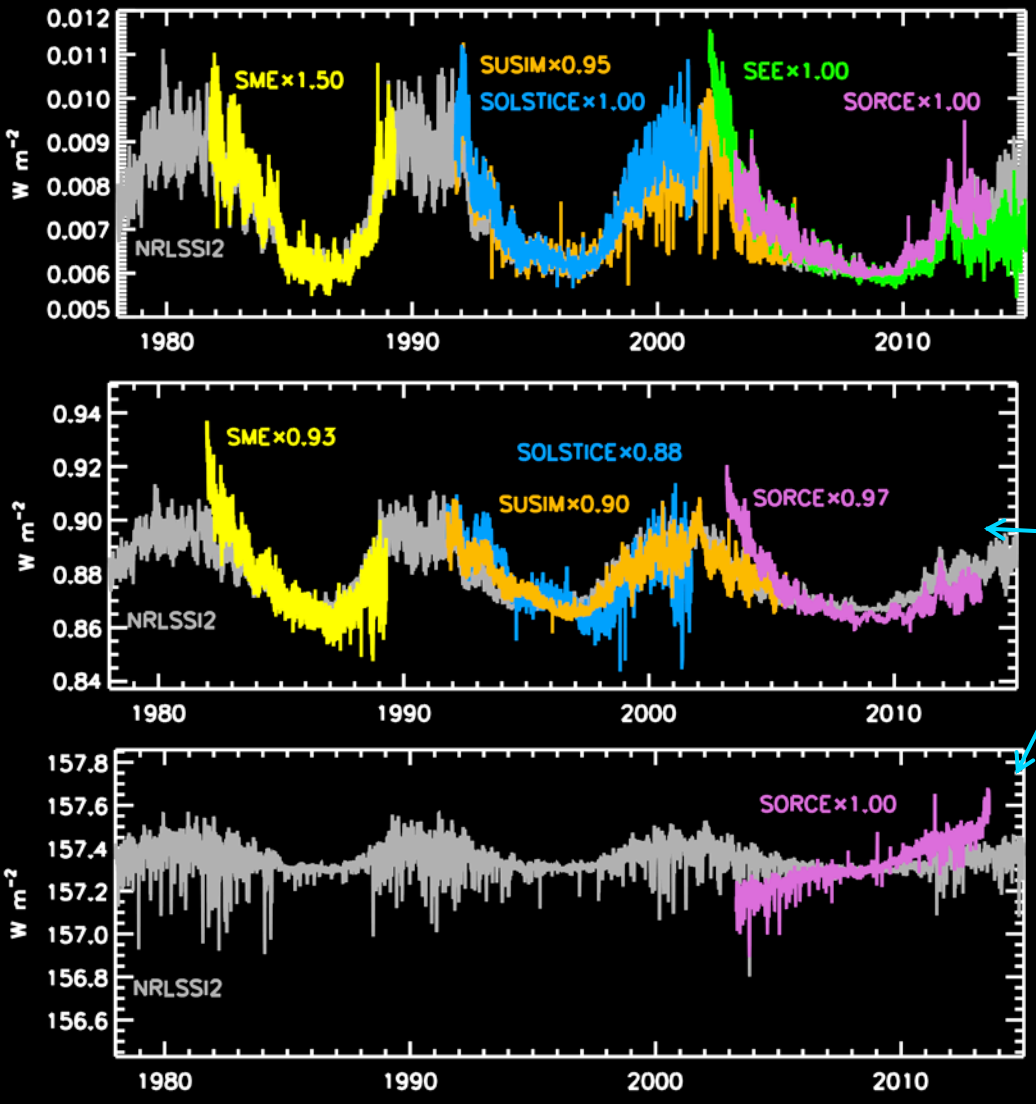
Solar Cycle 22

Solar Cycle Bolometric Faculae vs. UV

in three separate cycles, and in multiple different datasets, TSI corrected for sunspot darkening tracks HI Lyman α irradiance throughout the solar cycle ..... this should also be the case for UV irradiance at λ<300 nm ..... provides a constraint for instrumental sensitivity changes



Solar Cycle Spectral Irradiance Changes



individual measurements are scaled to NRLSSI2 absolute flux

HI Lyman α
121-122 nm

Middle Ultraviolet
220-240 nm

Compared with NRLSSI2 model SORCE/SIM solar cycle variations are:
- in-phase and larger at UV wavelengths
- larger and non-cyclic at VIS wavelengths

Visible-near IR
600-700 nm

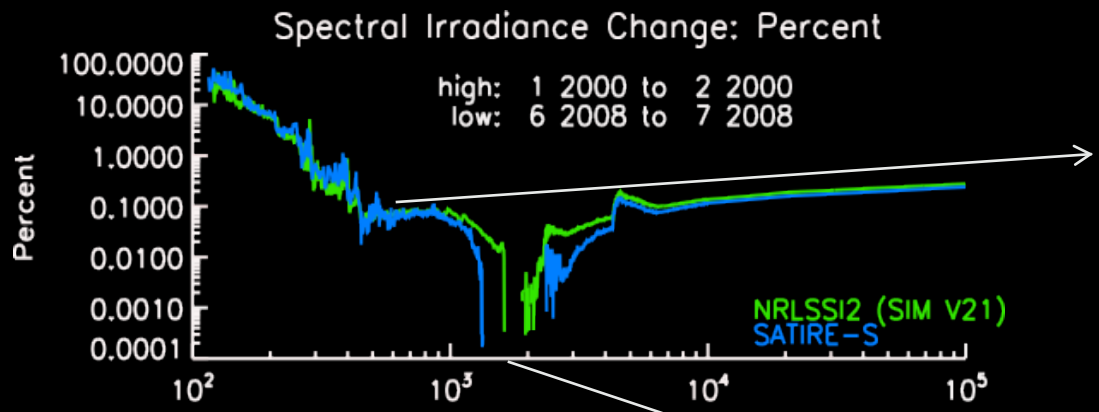
$$\int F(\lambda,t)d\lambda = TSI(t)$$

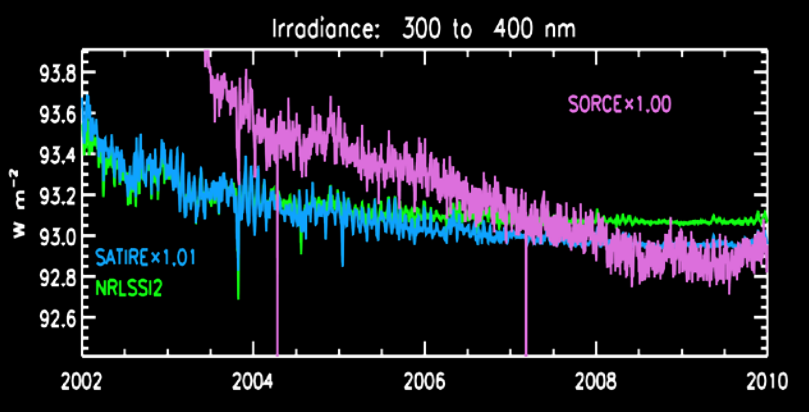
$$\int \Delta F_{facu}(\lambda,t)d\lambda = \Delta TSI_{fac}(t)$$

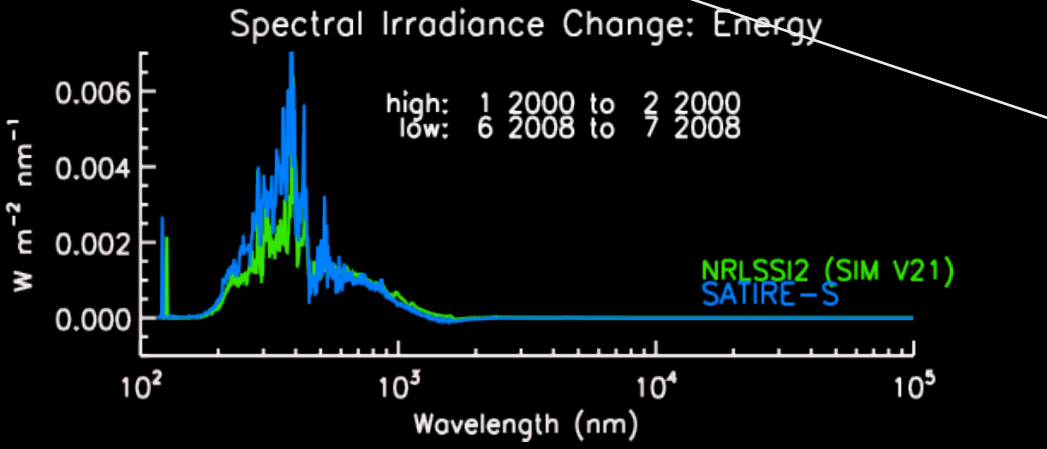
$$\int \Delta F_{spot}(\lambda,t)d\lambda = \Delta TSI_{spot}(t)r$$

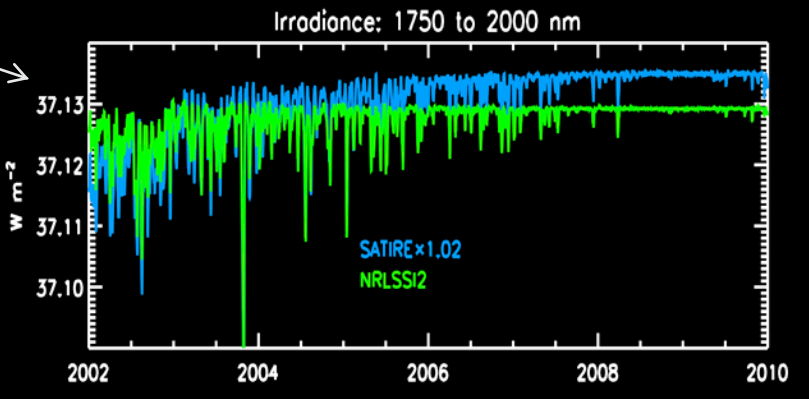
NRLSSI2 spectral irradiance variability model of faculae & sunspot influences is NOAA CDR

Solar Cycle Spectrum Changes







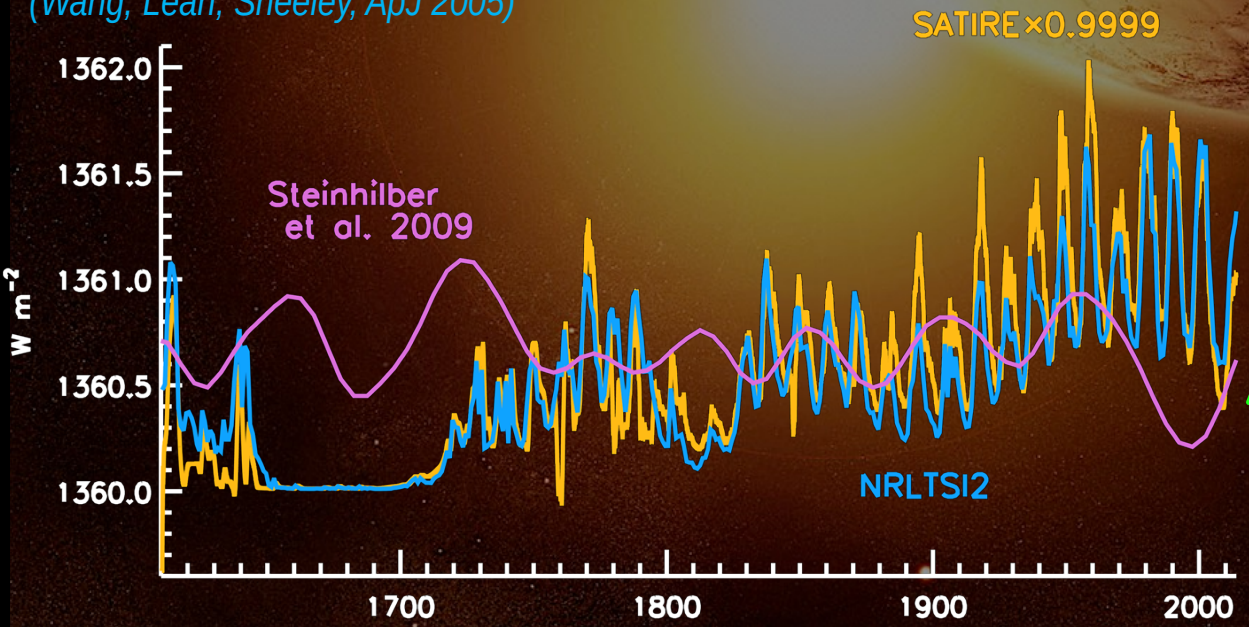


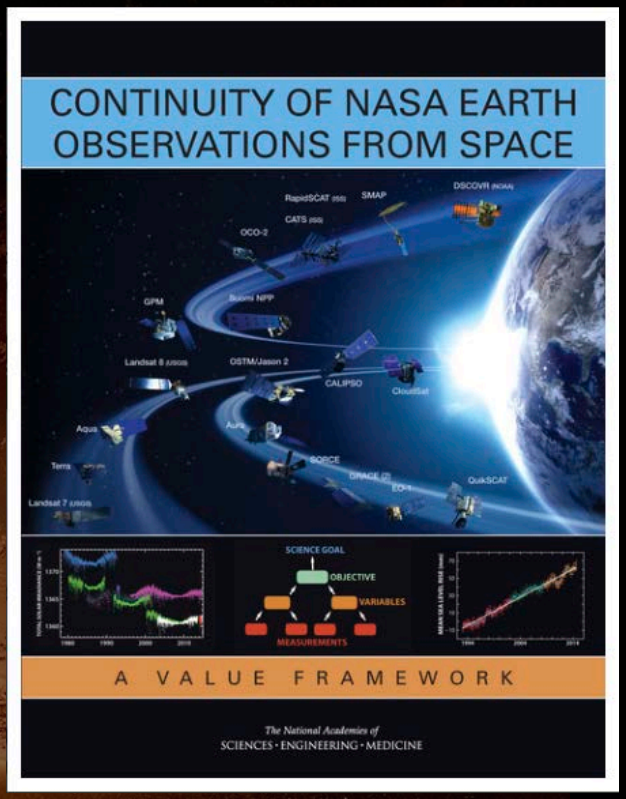
Since the sum of SSI must equal TSI, larger UV irradiance variability requires smaller visible-near IR irradiance variability & vice versa.

How Does the Sun's Spectrum Vary?

- Long Term – multiple decades
  - *does the Sun's irradiance have multi-decadal variability?*
  - *what is its plausible magnitude?*

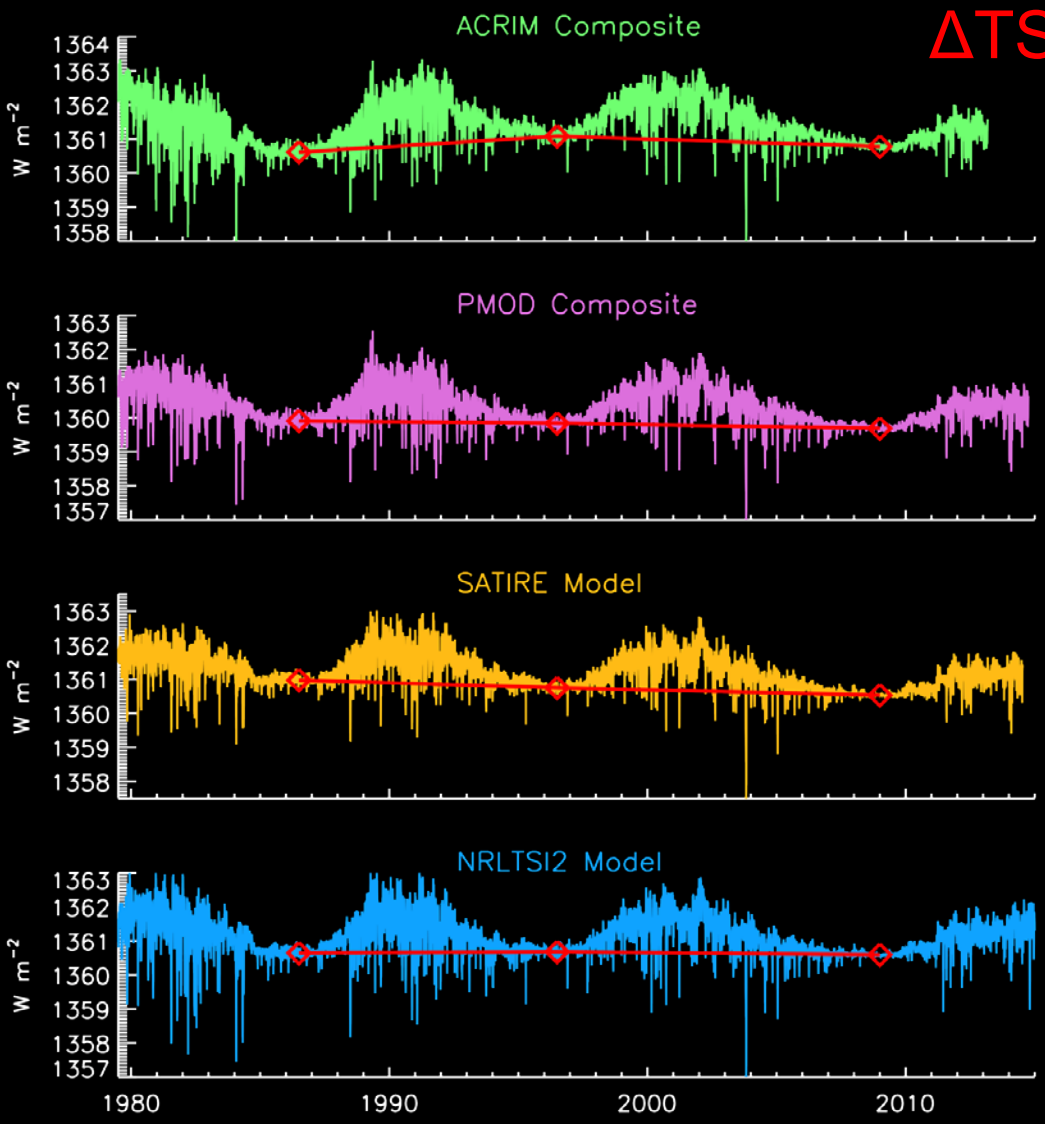
NRLTSI2 (& NRLSSI2) long-term trend based on NRL flux transport model calculations (Wang, Lean, Sheeley, ApJ 2005)





Climate records require continuous observations with NIST-traceable uncertainty and repeatability

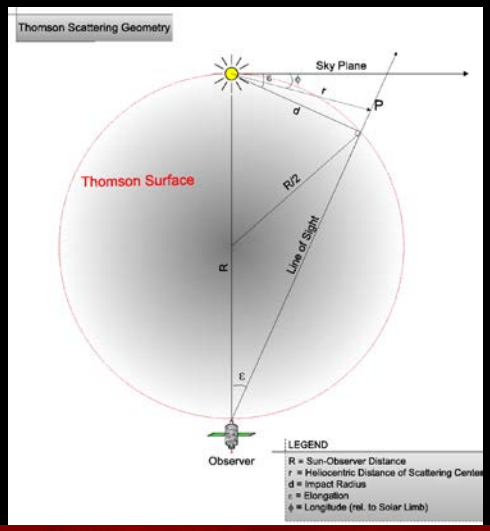
Inter-Minima Solar Irradiance Changes



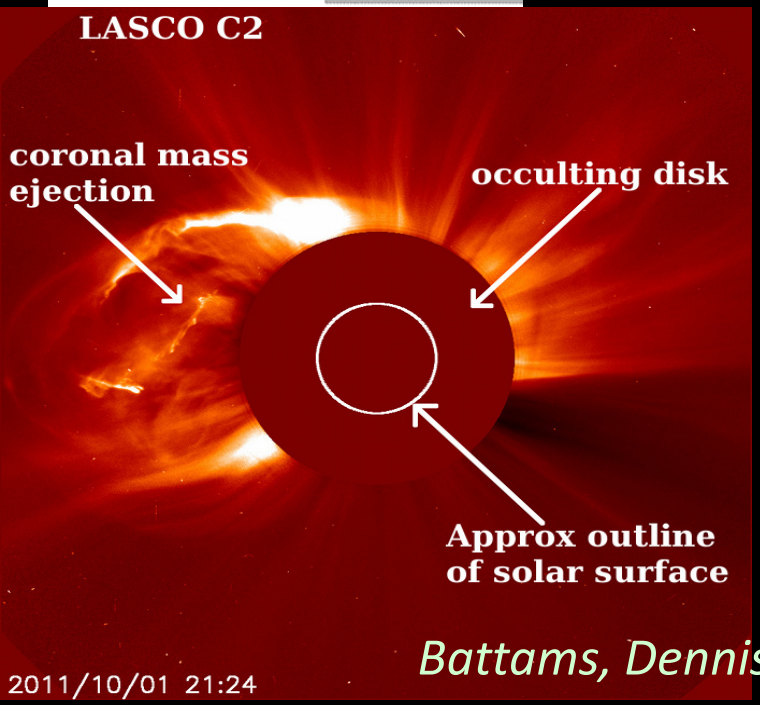
ΔTSI	1986.5-1996.5	1996.5-2009
ACRIM Composite	+0.47 (345 ppm/decade)	-0.30 (-176 ppm/decade)
PMOD Composite	-0.07	-0.15
SATIRE Model	-0.23	-0.22
NRLTSI2 Model	+0.03 (22 ppm/decade)	-0.08 (-47 ppm/decade)

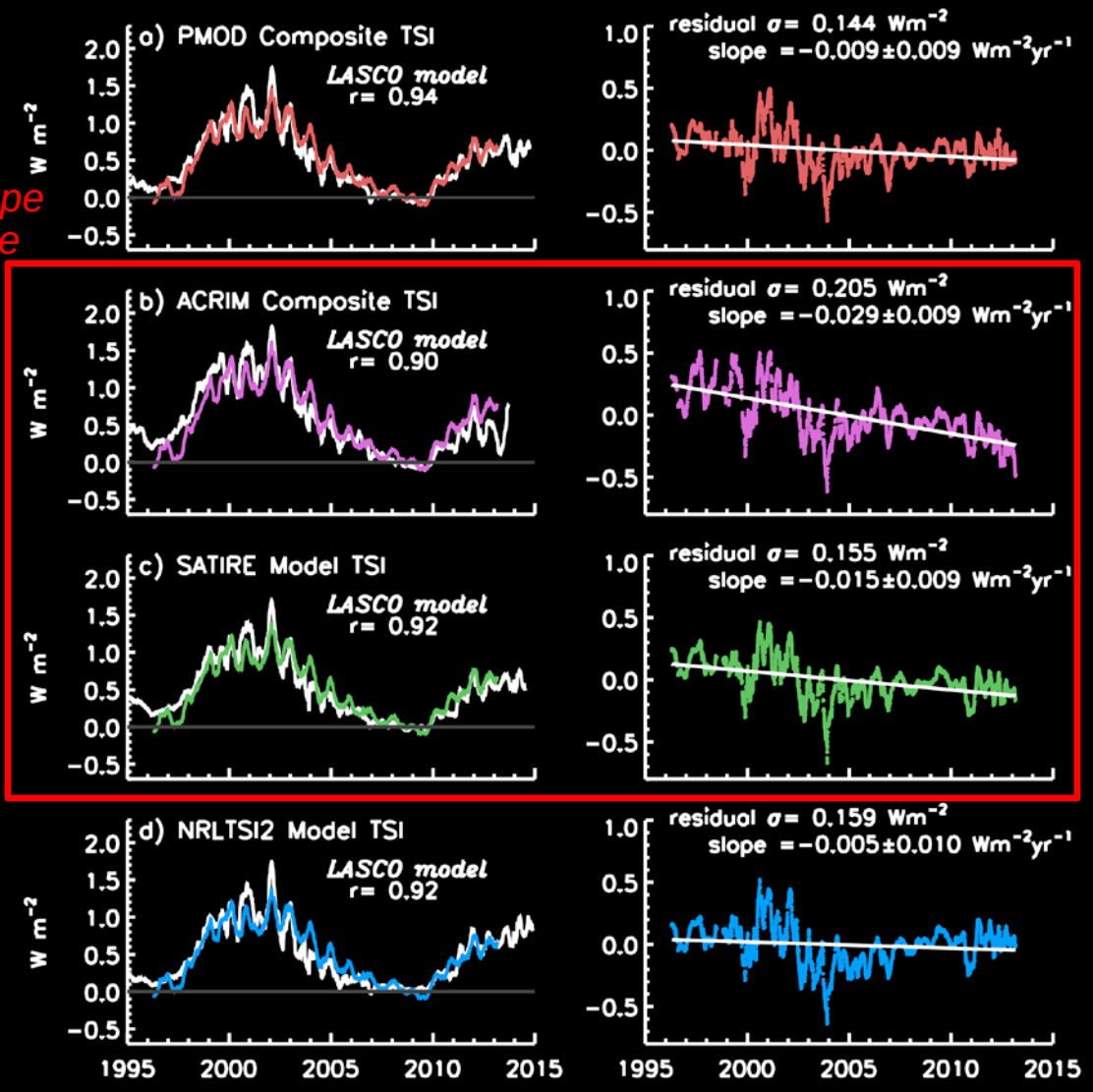
Wm^{-2}

A New Irradiance Index:
the global white-light corona observed by SOHO/LASCO



Long-term slope differences are significant





Battams, Dennison, Howard and Lean, Astrophys. J., submitted, 2016

How Does the Sun's Spectrum Vary? SUMMARY, Year 1

- Solar Rotation
  - *- sunspots and faculae cause solar rotational modulation of irradiance*
  - *- NRLSSI2 proxy model closely tracks observed rotational modulation*
  - *- SATIRE model overestimates rotational modulation at $\lambda < 400$ nm*
- Solar Cycle
  - *- sunspots and faculae cause solar irradiance 11-year cycles*
  - *- NRLSSI2 proxy model closely tracks observed TSI & Lyman α cycles*
  - *- bolometric facular signal tracks Lyman α (and UV) irradiance*
  - *- SATIRE model underestimates solar cycle 21 amplitude (factor of two)*
- Long Term
  - *- TSI observations disagree about inter-minim trends*
  - *- new white-light coronal irradiance index suggests ACRIM TSI inter-minim trend from 1996 to 2008 is too big*
  - *- TSI models disagree about inter-minim trends; SATIRE TSI too high in 1986 and therefore inter-minima trend is likely too big*

How Does the Sun's Spectrum Vary?
FUTURE WORK

- reprocess SME database with improved wavelength calibration and long term stability

- test the scaling of rotational modulation to solar cycle variability using reprocessed, improved SME database

- improve sunspot blocking parameterization – timing, small spots

- quantify bolometric faculae and UV irradiance relationship & uncertainty

- use newly constrained UV spectrum variability (from SME and bolometric faculae) to better constrain visible & near IR spectrum changes

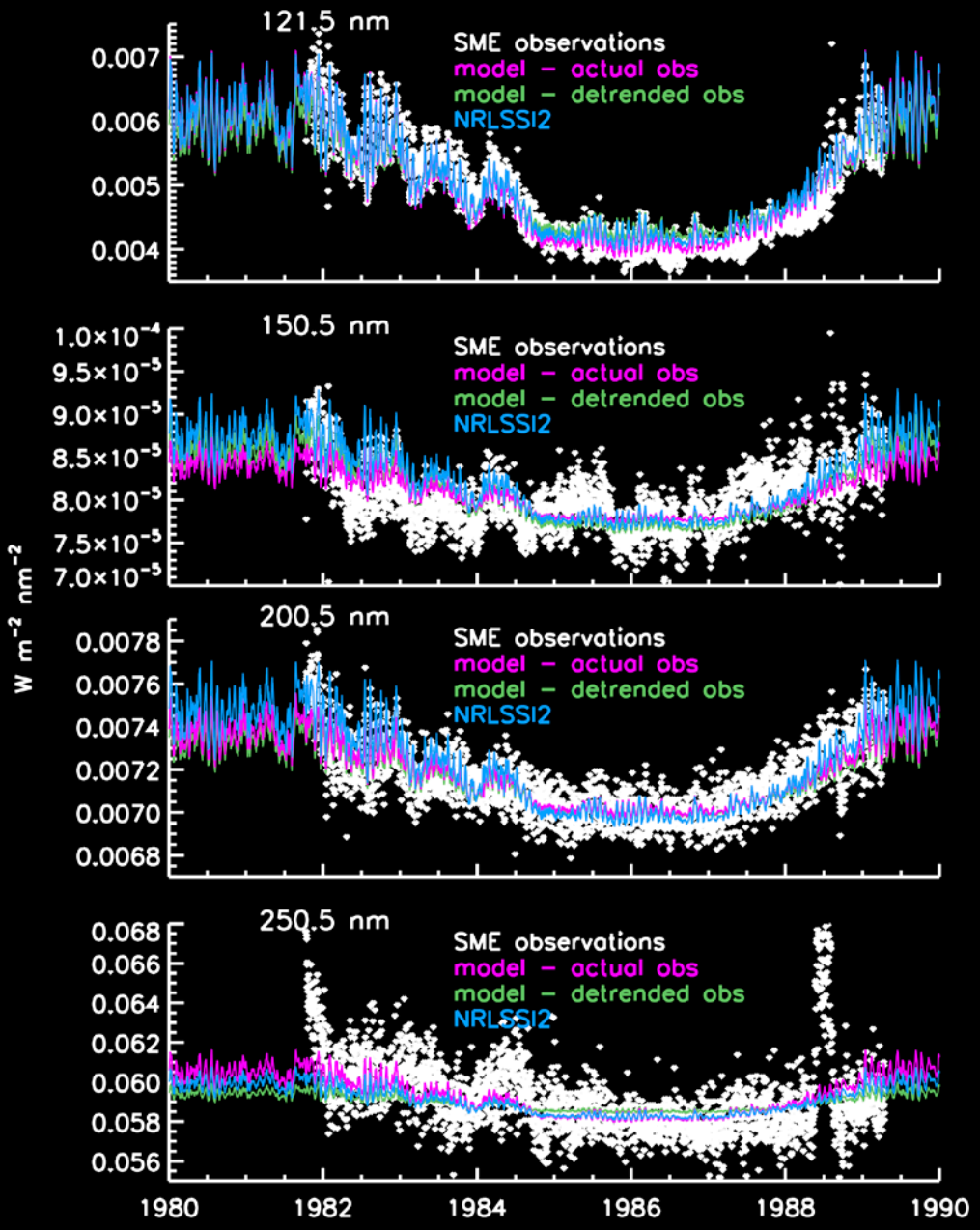
- extend LASCO coronal white light irradiance index to present

<u>In collaboration with other SIST teams</u>:

- incorporate new total solar irradiance composite to additionally constrain solar cycle spectrum changes

- analyze and compare facular component of new total solar irradiance composite

- compare new Lyman α composite with sunspot-corrected new total solar irradiance composite



Improved Certainty and Understanding from Reprocessed SME Database

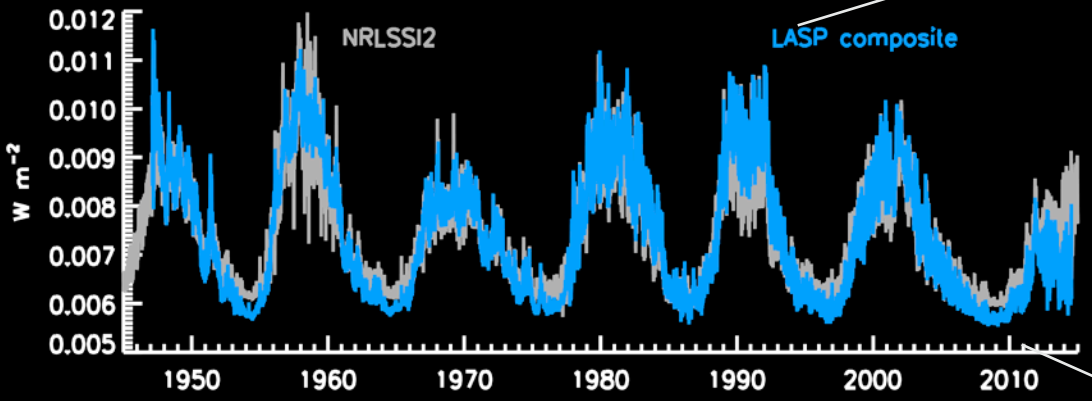
Spinning spacecraft – minimal solar exposure – small degradation - redundant diffusers

BUT –wavelength instability

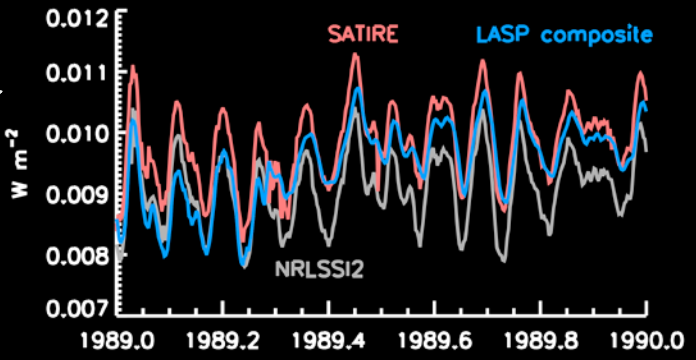
New determination of solar cycle UV irradiance change

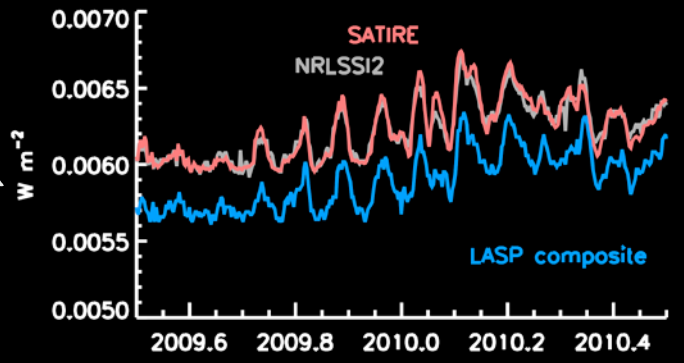
Test the assumptions of the NRLSSI model of solar-rotation to solar-cycle scaling.

Solar HI Lyman α Irradiance Variability

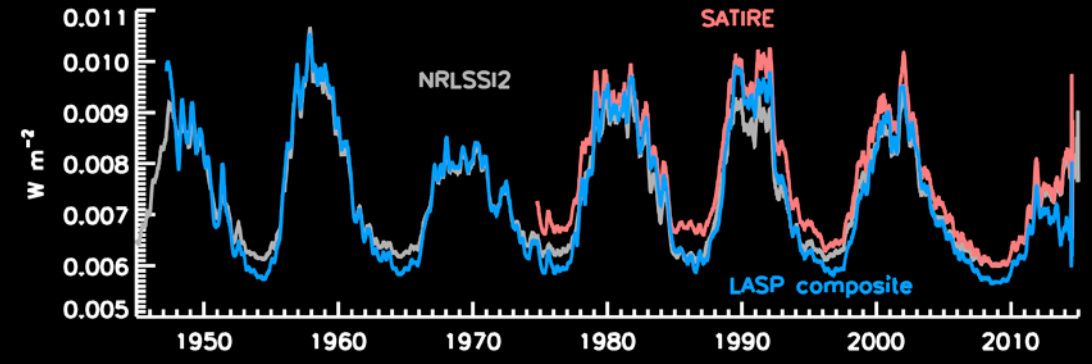


Solar Maximum





Solar Minimum



Observational composite has larger solar cycle amplitude than models

Models and observations have different trends at solar cycle minima