SATIRE-S Reconstruction of TSI & SSI Since 1974

What are some of the key issues regarding TSI & SSI variability?
What can we say about them through SATIRE-S?

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Background: TSI observations

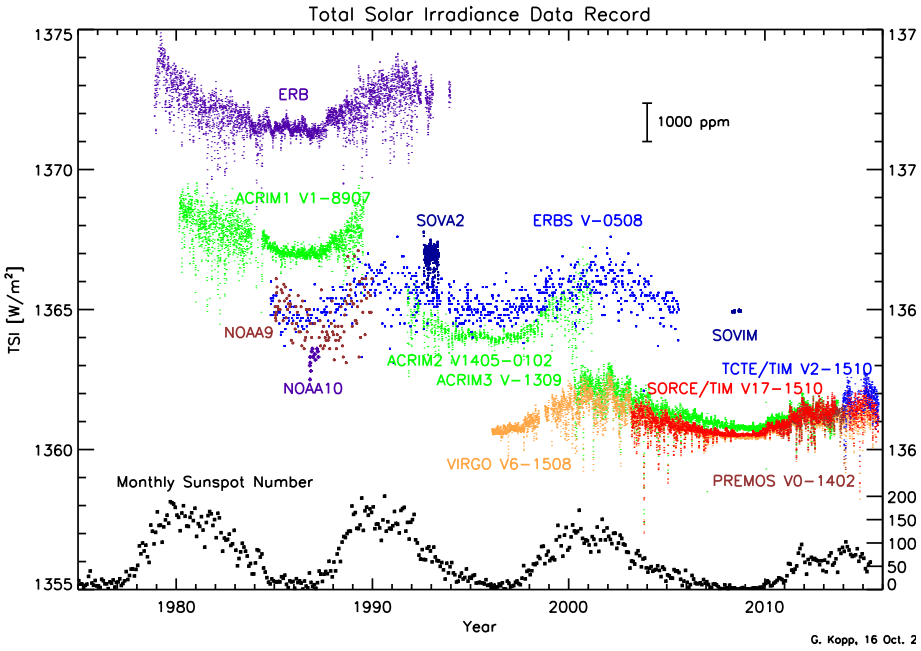


Figure 1 : TSI & sunspot number (spot.colorado.edu/∼koppg/TSI/).

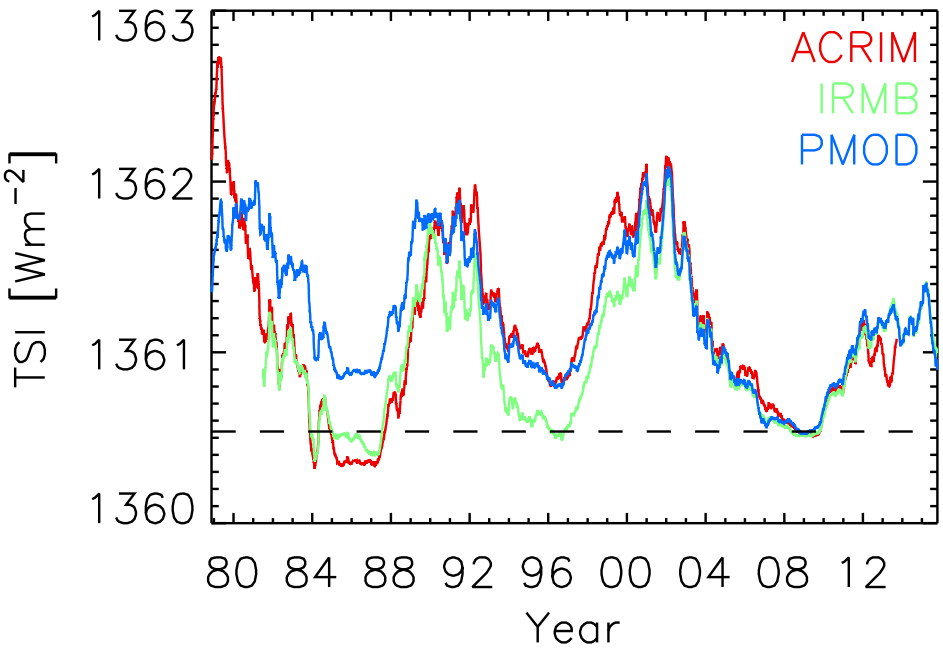


Figure 2 : TSI composites.

- Monitored from space since 1978. Reveal correlation with solar cycle.
- Calibration non-trivial. Uncertainty in absolute level & overall trend.
- Composites exhibit discrepant solar cycle amplitudes & secular trends.

Background: SSI observations

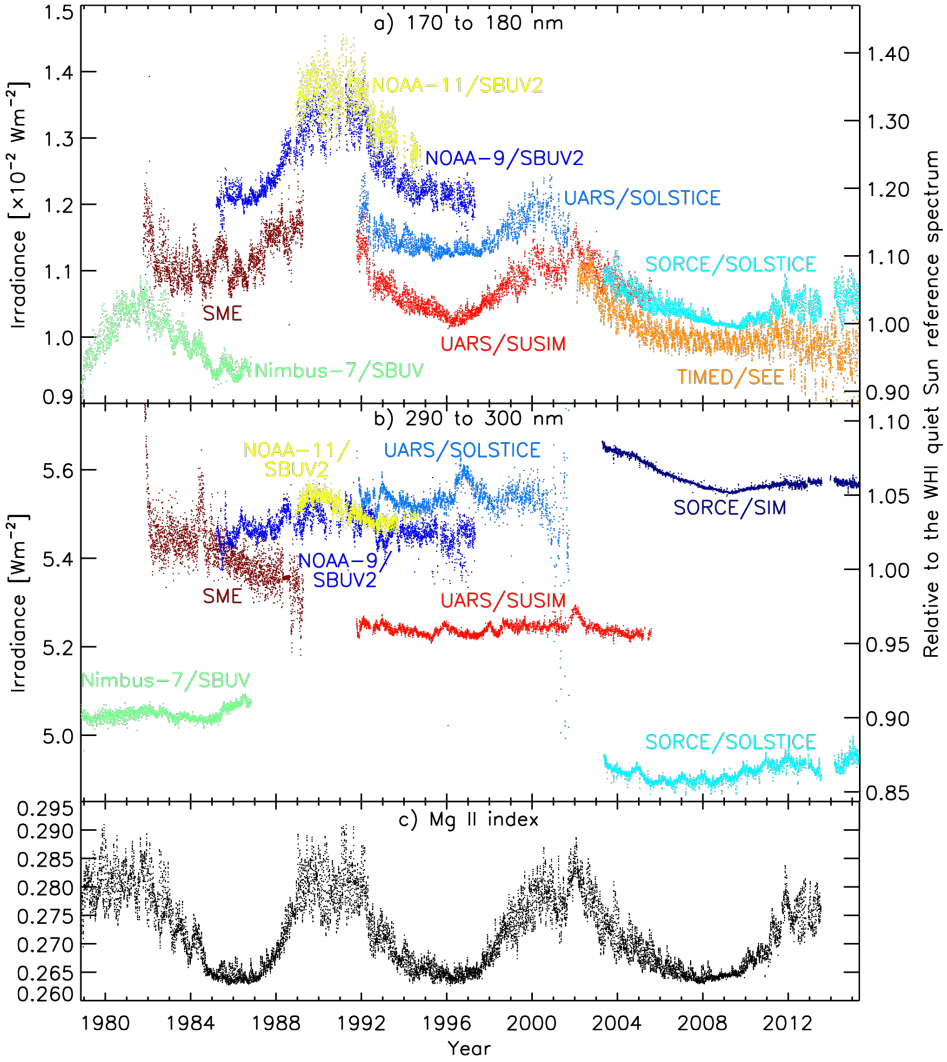


Figure 3 : UV SSI & Snow et al. 2005 Mg II index (Yeo et al. 2014).

UV (120 to 400 nm)

- Also monitored since 1978.
- Instrumental effects more severe (wavelength-dependent).
- Solar cycle variability $\sim 50\%$ at Lyman-α declining to $\sim 0.5\%$ above 300nm. Uncertainty in solar cycle variability above $\sim$240nm.

Visible/IR (>400nm)

- Only one monitoring mission so far (SORCE/SIM, launched 2003).
- Solar cycle variability conflicts with theory and models (see papers by Ball, Ermolli, Wehrli, Woods and Yeo et al.).

Why model TSI & SSI?

Satellite observations insufficient to build a complete picture of TSI & SSI variability.

- Extend just 4 solar cycles and not without gaps.
- Calibration non-trivial.
- Uncertainty in the secular trend & spectral-dependence of solar cycle variability.

Satellite observations are however accurate enough to reveal connections to solar magnetic activity, allowing us to reconstruct solar irradiance relating the variability to solar magnetism.

Two modelling approaches.

- **Proxy**:Fit indices of solar magnetic activity to measured TSI & SSI.
- **Semi-empirical**:Reconstruct solar spectrum from intensity spectra of solar surface features.

Modelling solar irradiance: Proxy approach

Fitting indices of magnetic activity to measured TSI & SSI is an obvious & straightforward way to reconstruct solar irradiance but not without limitations.

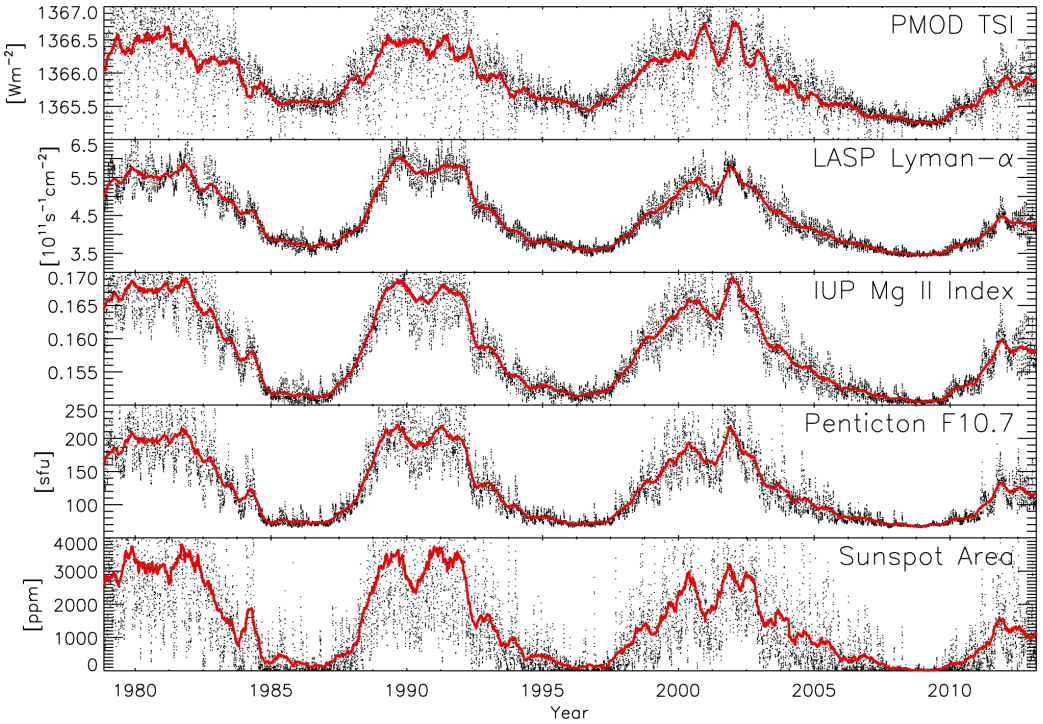


Figure 4 : TSI and indices of solar magnetic activity.

- Can we use the index formed at a particular height in the solar atmosphere to represent TSI or SSI formed at other heights?
- Is it OK to assume linear & consistent relationship between indices and solar irradiance?
- Affected by measurement uncertainty in index and solar irradiance data.
- Not possible at all wavelengths (limited reliable SSI measurements).

Modelling solar irradiance: Semi-empirical approach

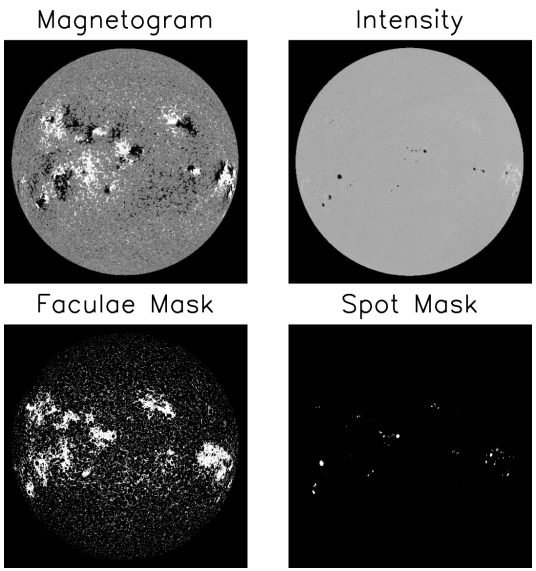
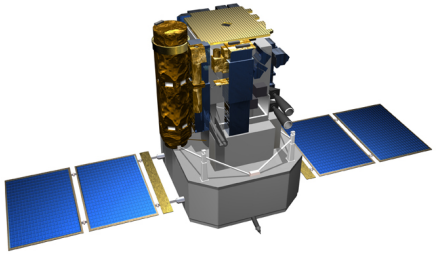


Figure 5 : Identifying faculae & sunspots by the magnetogram signal & intensity.

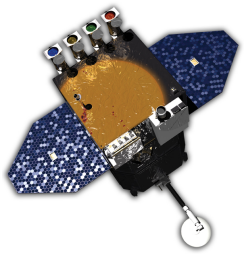
SATIRE-S: Spectral And Total Irradiance REconstruction for the Satellite era (Krivova et al. 2003; Yeo et al. 2014)

- Solar surface =
  Quiet Sun (Q) + Faculae (F) + Sunspots (S)
- Surface coverage of Q/F/S from full-disc intensity images & magnetograms.
- Intensity spectra of Q/F/S from model solar atmospheres & radiative transfer code (Unruh et al. 1999).
- Solar spectrum given by surface coverage weighted sum of Q/F/S intensity spectra.

Kitt Peak Vacuum Telescope
(1974 - 2003)



SoHO/MDI
(1996 - 2011)



SDO/HMI
(2010 - present)

Modelling solar irradiance: Semi-empirical approach

Other semi-empirical models reported in the literature.

- SRPM (Fontenla et al. 1999/2009/2011/2015)
- OAR (Penza et al. 2003; Ermolli et al. 2003/2011/2013)
- PMOD (Shapiro et al. 2010/2013)

Presently, SATIRE-S is the only semi-empirical model to provide reconstructions of TSI and UV to IR SSI spanning the entire period of satellite observation at daily cadence.

Key issues: Secular trend

Models, proxy or semi-empirical, can recover $> 90\%$ of the variability in measured TSI.

Proxy

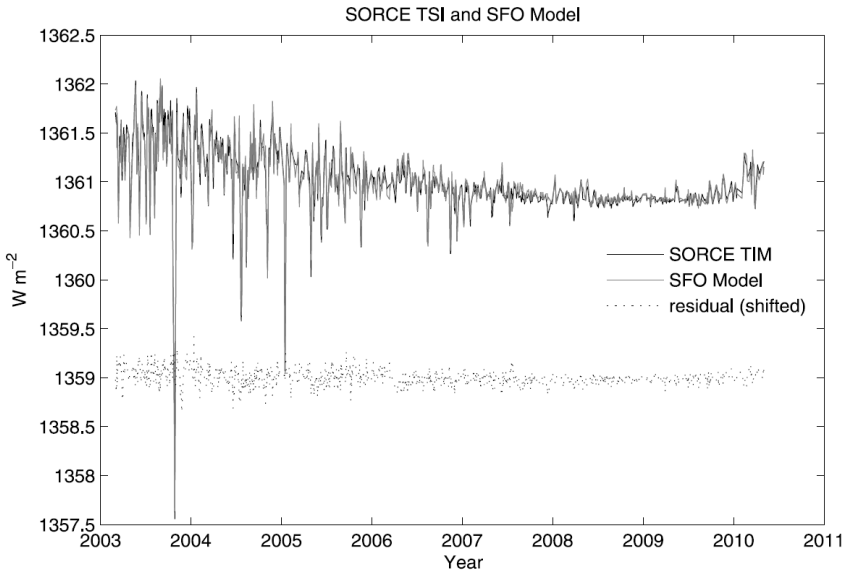


Figure 6 : SFO TSI (Chapman 2012).

Semi-empirical

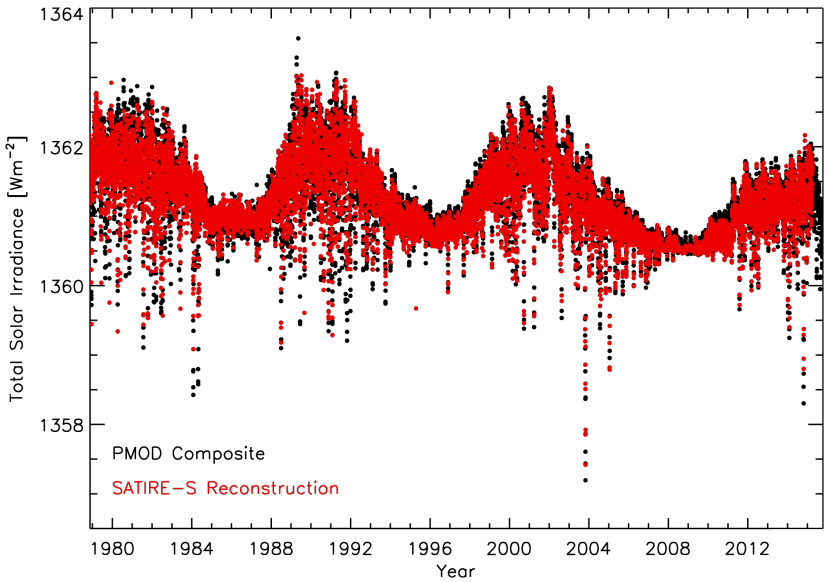


Figure 7 : SATIRE-S TSI.

There remains, however, controversy over the secular trend.

Key issues: Secular trend

SoHO/VIRGO TSI

- VIRGO record only (aside from ERBE) to extend two solar cycle minima (1996 and 2008).
- Indicates min.-to-min. decline of 0.2 Wm^{-2} (one-fifth of the cycle amplitude).

Mg II index

- Line core-to-wing ratio at the Mg II h & k doublet about 280nm.
- Widely employed in proxy models as proxy of faculae brightening.

Proxy models based on the Mg II index cannot reproduce the min.-to-min. decline in VIRGO TSI. Is the secular decline in VIRGO TSI real?

Key issues: Secular trend

TSI

- Three published composites (upcoming: SOLID) with conflicting secular trends.
- IRMB: No min.-to-min. trend.
- PMOD (which uses VIRGO TSI after 1996): Clear min.-to-min. decline.

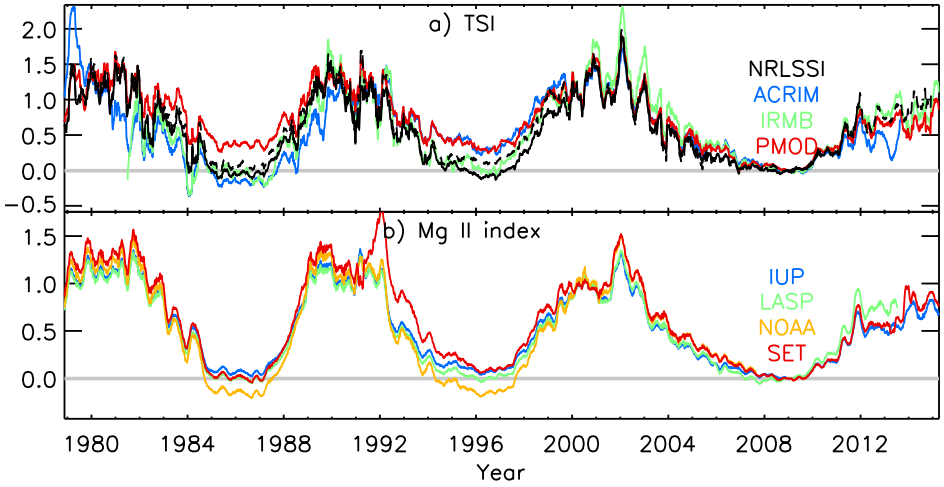


Figure 8 : TSI and Mg II index (stretched between 0 and 1 at 2008 minimum and 2000 maximum).

NRLSSI (solid) & NRLSSI2 (dash) (Lean et al. 1997, 2000; see also talk by Odele Coddington)

- Proxy model based on the Mg II index.
- Consistent with IRMB composite.
- Available Mg II index composites exhibit vastly different secular trends.
- Can we trust the secular trend in proxy models based on the Mg II index?

Key issues: Secular trend

TSI

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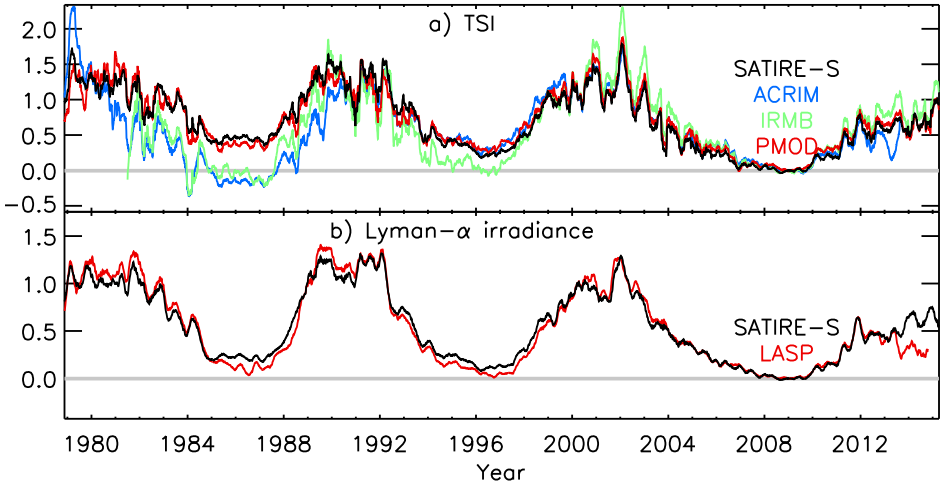

Figure 9 : TSI and Lyman-α irradiance (stretched between 0 and 1 at 2008 minimum and 2000 maximum).

SATIRE-S

- Consistent with PMOD composite.
- Consistent with Lyman-α irradiance.

Key issues: Secular trend

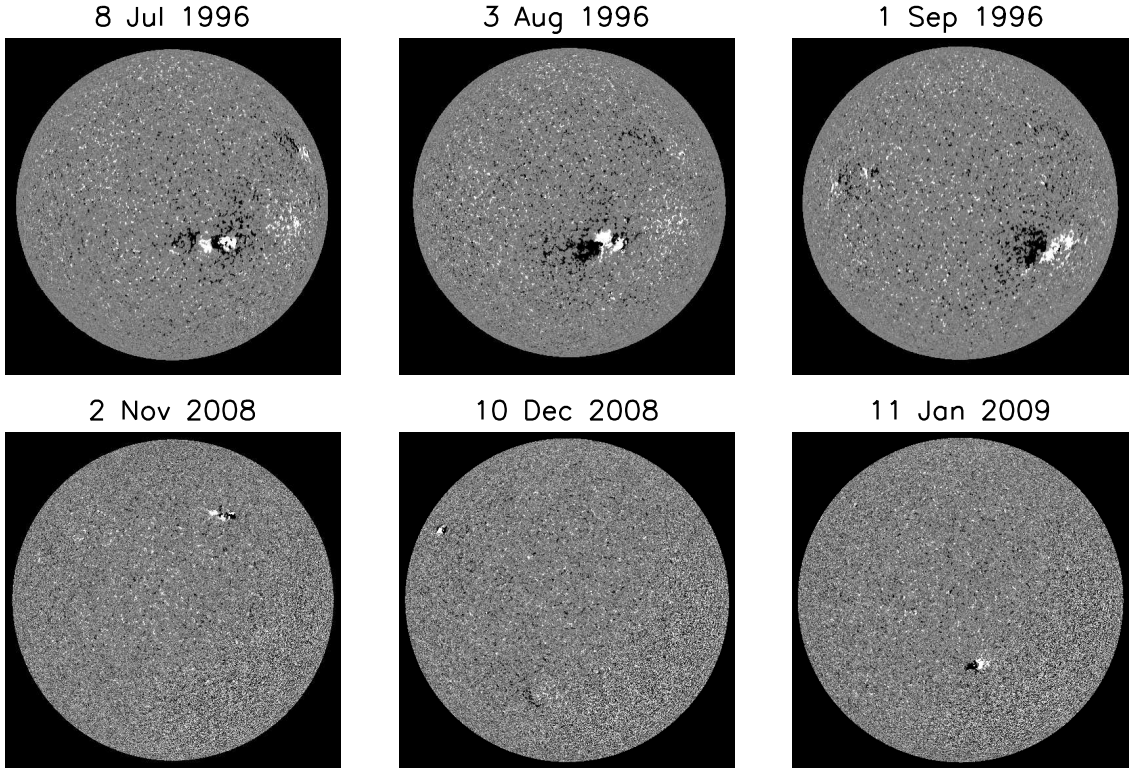

Figure 10 : Magnetogram from most active day each calendar month about the 1996 and 2008 minima.

Where does the secular decline in SATIRE-S come from?

SATIRE-S is based on full-disc magnetograms, where the Sun is visibly & indisputably more active at the 1996 minimum compared to the 2008 minimum.

Key issues: Secular trend

Can we see a secular decline anywhere else?

- Sunspot number and SFO facular excess exhibit clear min.-to-min. decline.
- Model based on sunspot area produces PMOD-like min.-to-min. decline.

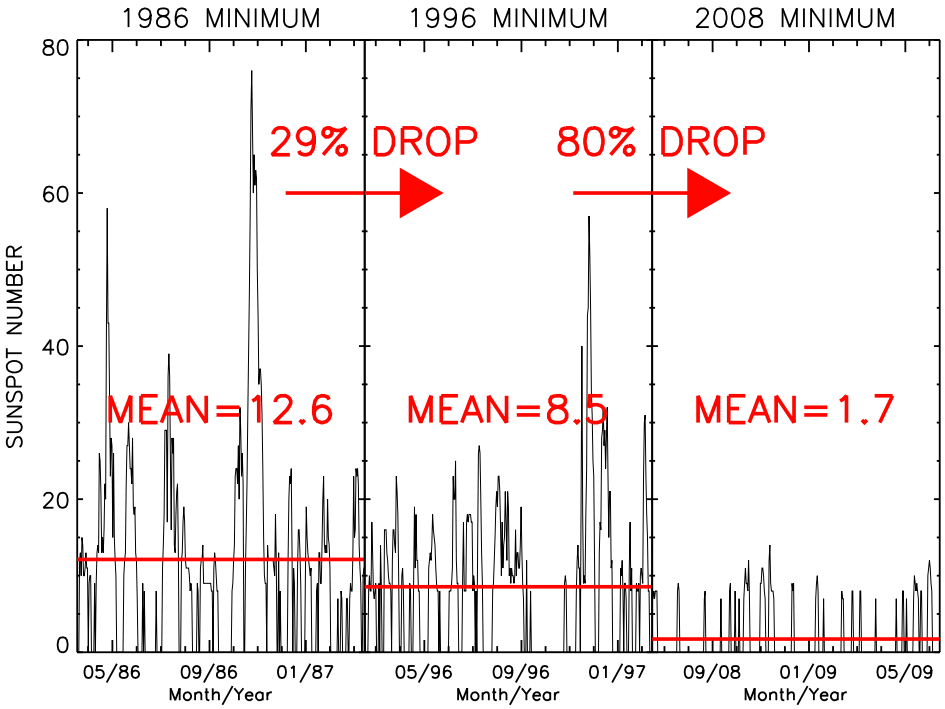

Figure 11 : Sunspot number about the 1986, 1996 and 2008 minima.

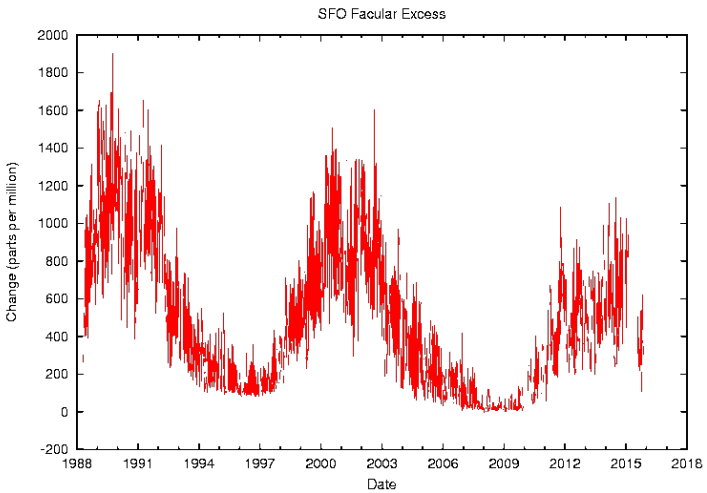

Figure 12 : SFO facular excess index (http://www.csun.edu/sfo/).

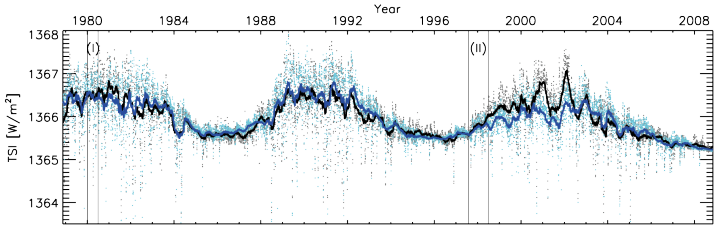

Figure 13 : TSI reconstruction based on sunspot area (SATIRE-T2, blue) and PMOD composite (black) (Dasi-Epuig et al. 2014).

Key issues: Secular trend

Evidence for secular decline not unassailable but certainly strong enough that it should not be ignored.

Key issues: Solar cycle variability in UV SSI

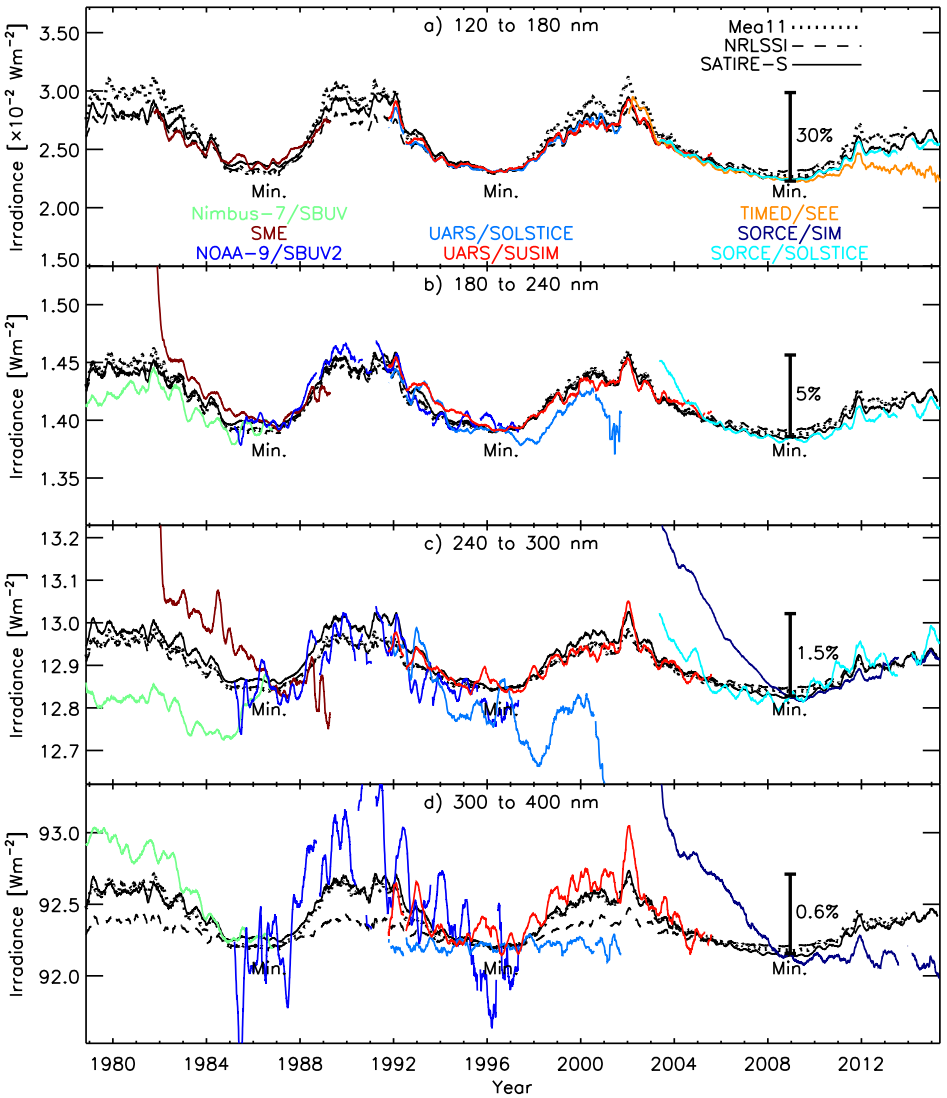

Figure 14 : Measured (colour) and reconstructed (black) UV SSI (Yeo et al. 2015).

- Morrill et al. 2011 (Mea11) - Fit Mg II index to UARS/SUSIM SSI.
- NRLSSI (Lean et al. 1997/2000) - Fit Mg II index & PSI to rotational variability in UARS/SOLSTICE SSI.
- SATIRE-S

Agreement between the various records and reconstructions deteriorates with wavelength. Why?

Key issues: Solar cycle variability in UV SSI

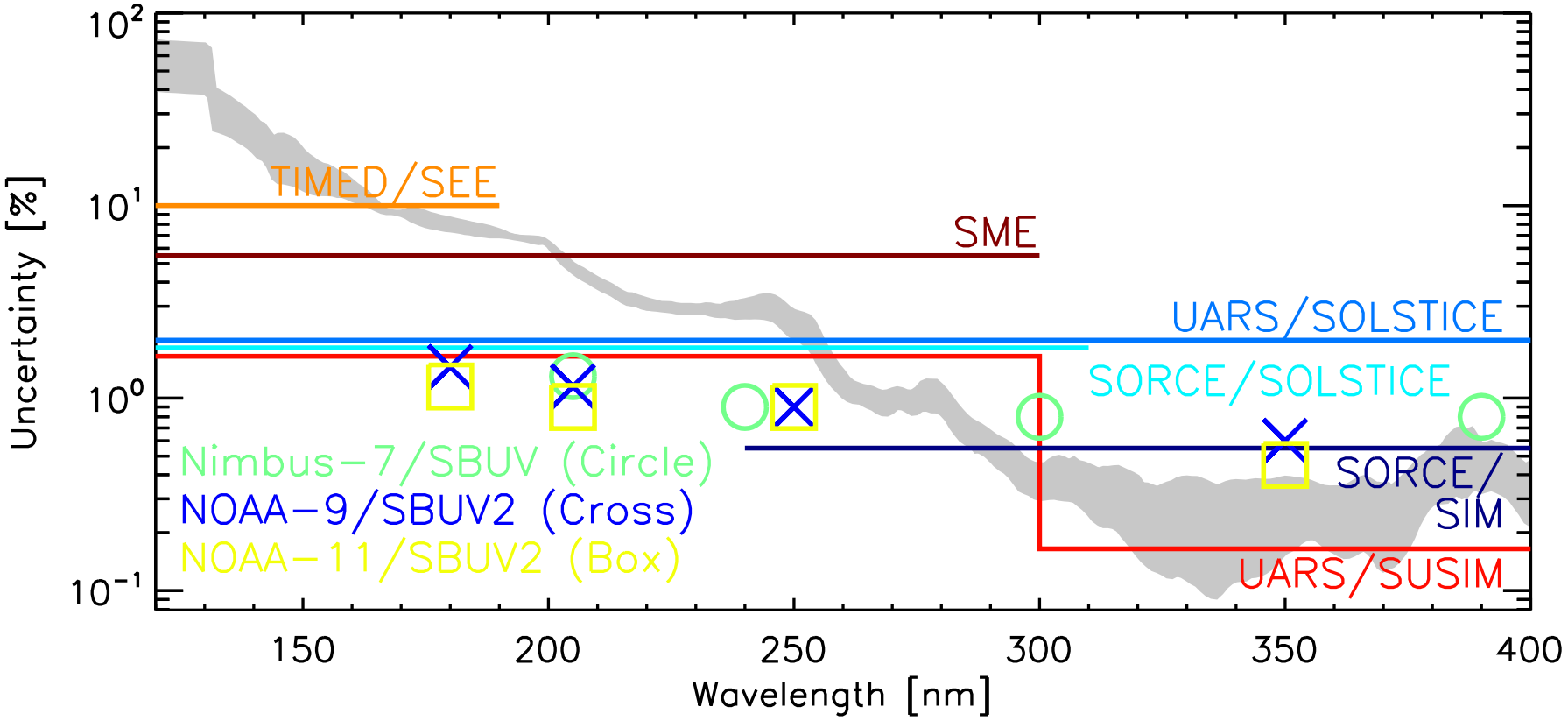

Figure 15 : Long-term uncertainty in measurements (colour) and solar cycle amplitude in models (grey) (Yeo et al. 2015).

Solar cycle variability weakens with wavelength. For certain instruments, solar cycle variability declines, towards longer wavelengths, below the limits of measurement stability.

Key issues: Solar cycle variability in UV SSI

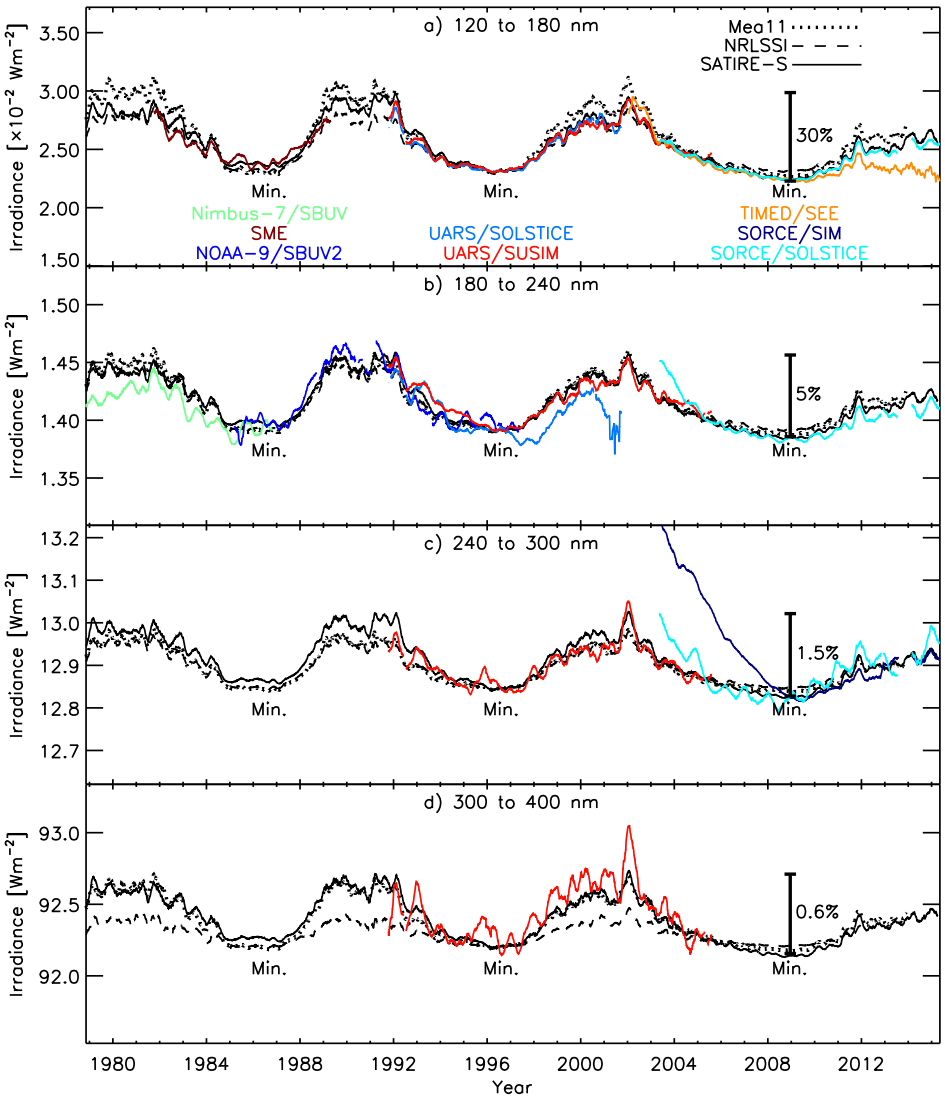

Figure 16 : Measured (colour) and reconstructed (black) UV SSI.

Excluding measurements where uncertainty > variability, agreement between observations and reconstructions not that bad after all! Up to 300 nm, models fairly consistent with measurements and with one another. Above 300 nm, solar cycle amplitude in NRLSSI markedly weaker.

On a side note...

Marked decline in SIM UV SSI between 2003 and 2008 is likely instrumental in origin (see papers by Ball, Deland, Ermolli, Lean, Morrill, Wehrli, Woods and Yeo et al.).

Key issues: Solar cycle variability in UV SSI

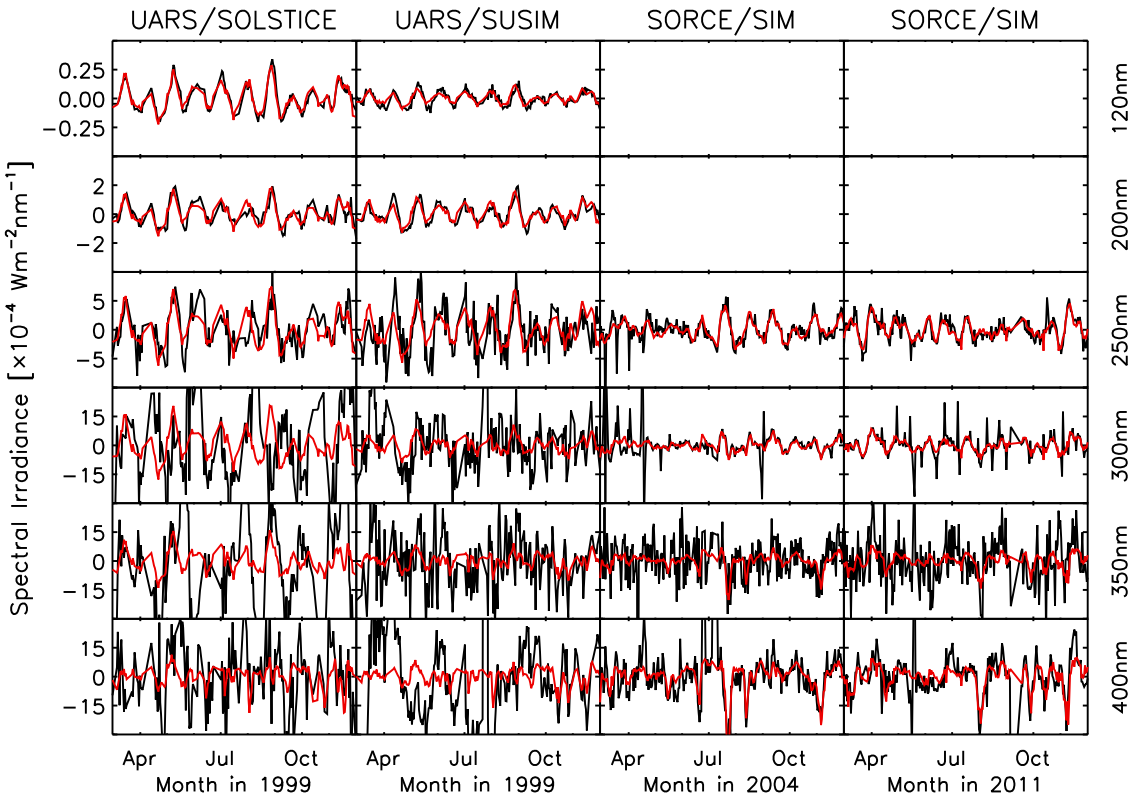

Figure 17 : Regression of Mg II index & PSI rotational variability (red) to SSI rotational variability (black).

NRLSSI and similar models based on fitting rotational variability in indices (red) to that in SSI (black). Above ∼300nm, agreement deteriorates due to noise. Can we trust the result here?

Key issues: Solar cycle variability in UV SSI

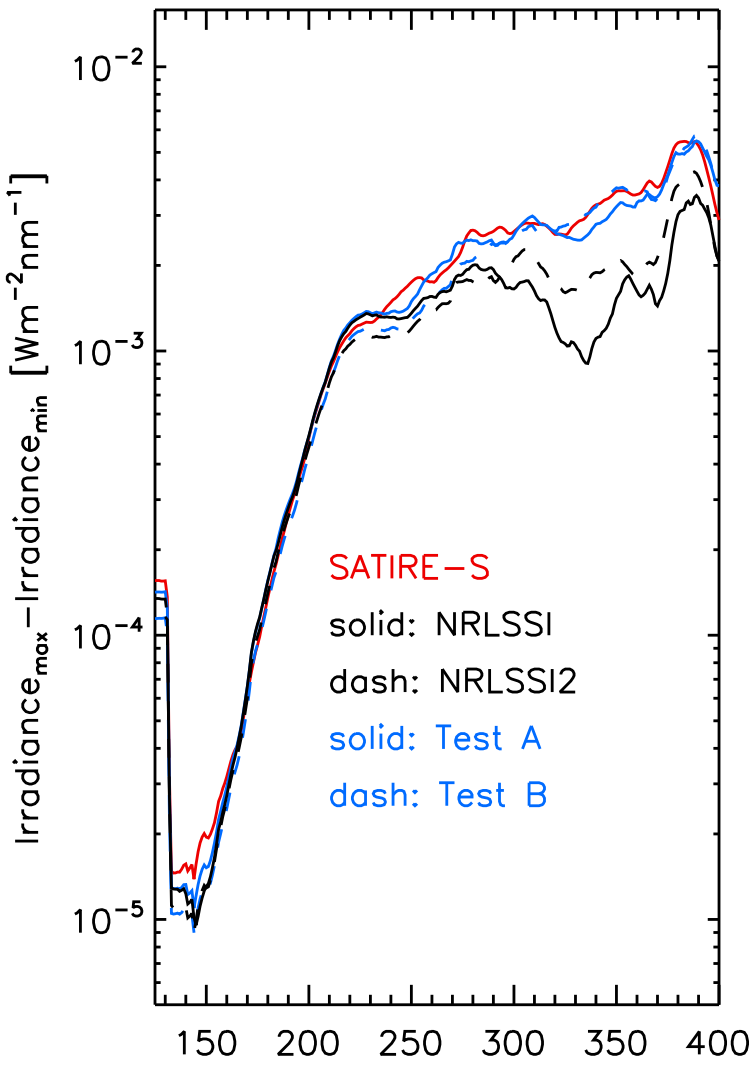

Figure 18 : Change in SSI between the 1996 minimum and 2000 maximum.

NRLSSI(2)

Fit Mg II index & PSI to UARS/SOLSTICE & SORCE SSI rotational variability.

Test reconstruction A

Fit Mg II index & PSI to UARS & SORCE SSI rotational variability taking measurement noise into account (Orthogonal Distance Regression).

Test reconstruction B

Fit Mg II index & PSI to UARS & SORCE SSI rotational variability denoised using a non local means filter.

If we take care of measurement noise, solar cycle variability derived from observed rotational variability becomes consistent with SATIRE-S.

Summary

Models replicate most of the variability in TSI and certain SSI records but there is still debate over...

Is there a secular decline over the past two to three minima?

- Secular decline in PMOD TSI and Lyman-α irradiance broadly replicated in SATIRE-S. Secular decline in solar activity evident in full-disc magnetograms, sunspot number, SFO facular excess and TSI model based on sunspot area.
- Evidence for secular decline is not unassailable but cannot be ignored either.

Why does the UV SSI variability in proxy and semi-empirical models differ?

- Applying NRLSSI approach of proxy modelling to UARS and SORCE UV SSI while taking measurement noise into account reproduces SATIRE-S-like variability.
- Discrepancy between NRLSSI(2) and SATIRE-S is from NRLSSI(2) not taking care of measurement noise in the regression. Done right, proxy and semi-empirical modelling of UV SSI are mutually consistent.