Solar Irradiance Variability & Solar Magnetism

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29 October 2018

MAX-PLANCK-GESELLSCHAFT

What is 'solar irradiance' & why should we care?

Solar radiative flux described in terms of...

- total flux: Total Solar Irradiance, TSI (W/m^2)
- spectral flux: Spectral Solar Irradiance, SSI $(W/m^2/nm)$

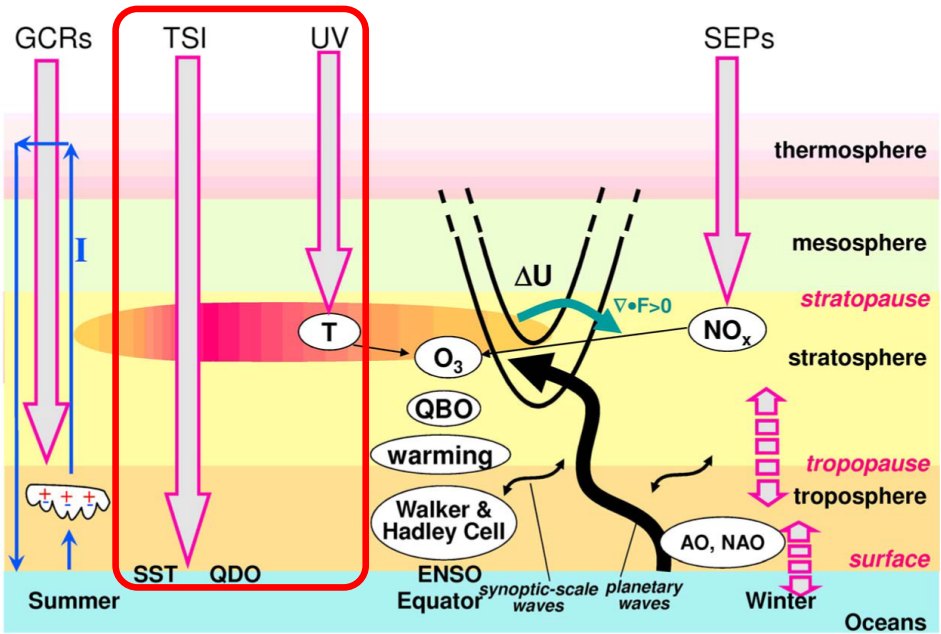


Figure 1: Mechanisms by which solar variability may influence the Earth's climate (Gray et al. 2010).

Influence on Earth's climate

- 'top-down' & 'bottom-up' mechanisms
- TSI & SSI variability, especially in the UV, important.

Measurement of TSI

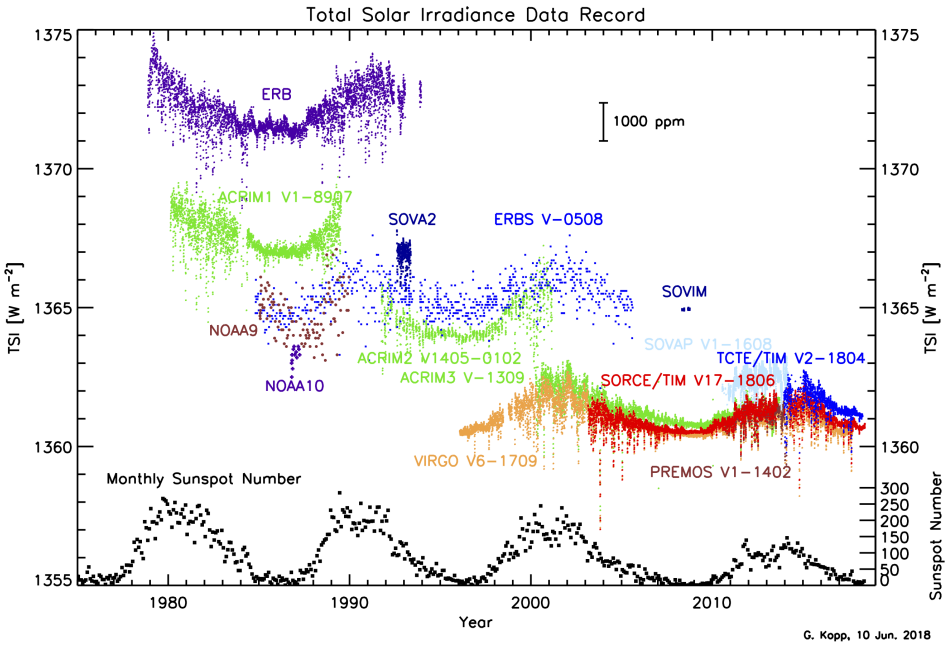


Figure 2: TSI & sunspot number (spot.colorado.edu/∼koppg/TSI/).

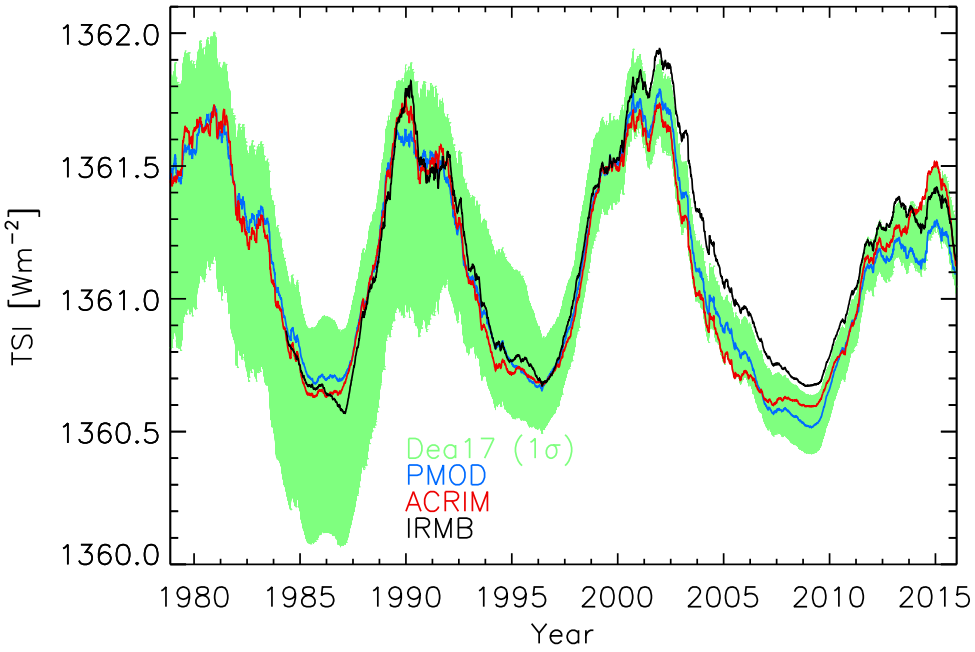


Figure 3: TSI composites.

- Monitored from space since 1978. Reveal correlation with solar cycle.
- Calibration issues.
- Composites exhibit discrepant decadal trends.

Measurement of SSI

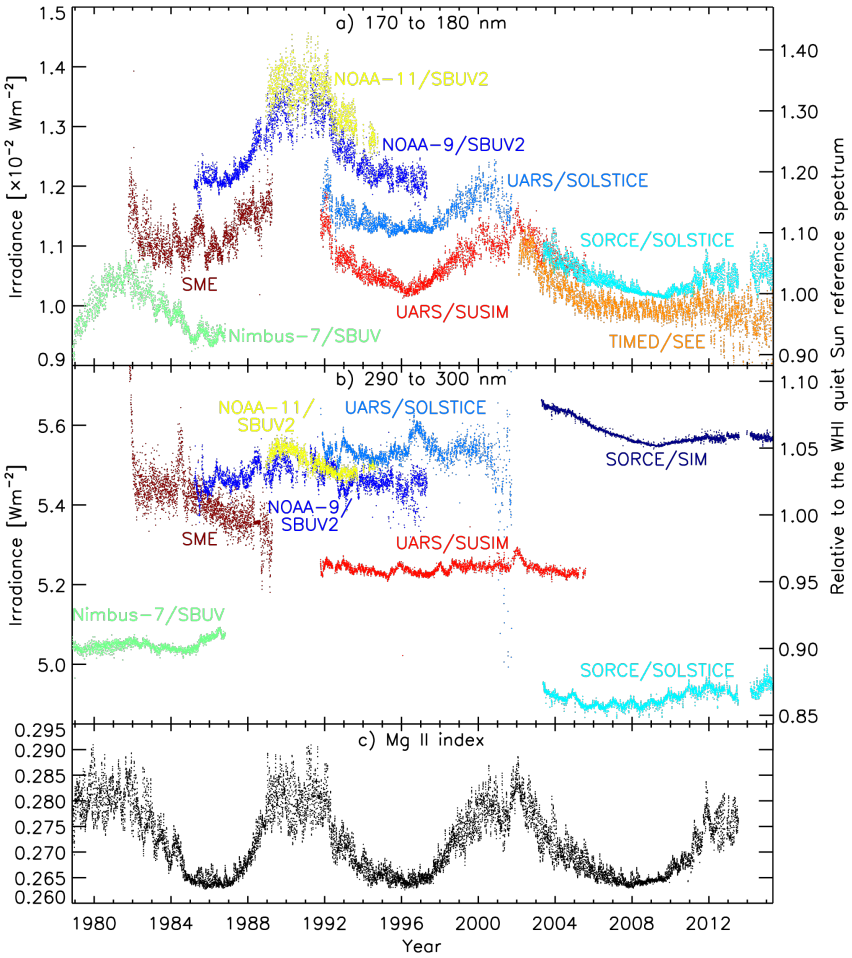


Figure 4: UV SSI & Snow et al. 2005 Mg II index (Yeo et al. 2014).

UV (120 to 400nm)

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

Visible & IR (>400nm)

- Only monitored since 2003 (SIM instruments on SORCE & ISS/TSIS).
- SORCE/SIM solar cycle variability conflicts with theory & models (see papers by Ball, Ermolli, Wehrli, Woods and Yeo et al.).

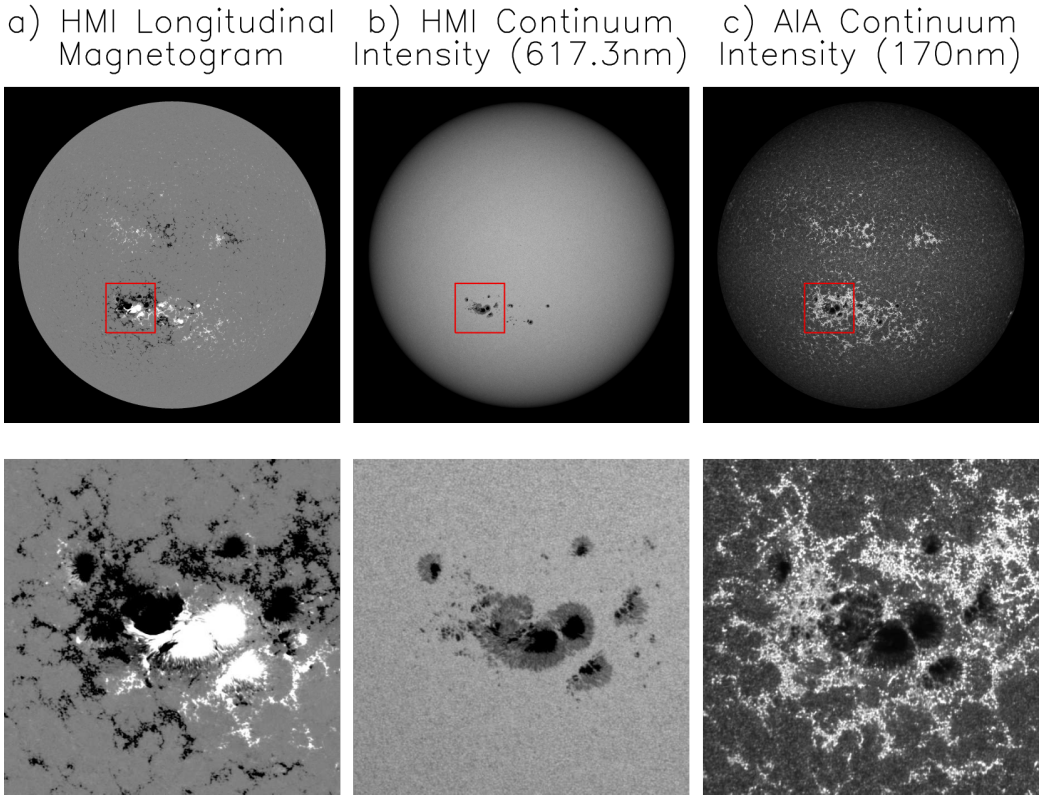
Satellite observations insufficient to build a complete picture of TSI & SSI variability.

- Extend just 4 solar cycles & with gaps.
- Calibration issues.
- Uncertainty in the decadal trend & wavelength-dependence of solar cycle variability.

However, satellite observations are accurate enough to suggest connections to the solar cycle, allowing us to reconstruct TSI & SSI by relating the variability to solar magnetism.

Two modelling approaches:

Proxy	Extrapolate measured TSI & SSI by the regression of indices of solar magnetic activity.
Semi-empirical	Reconstruct solar spectrum from surface coverage & intensity spectra of solar surface structures.



How does solar magnetism modulate solar irradiance?

- Cyclic emergence/evolution of magnetic concentrations on the solar surface.
- Affects temperature structure & radiant behaviour of enclosed solar surface/atmosphere.
- Prime candidate driver of solar irradiance variability at timescales greater than a day.

Figure 5: Active region NOAA 11520, 11 July 2012(Yeo et al. 2014).

Modelling solar irradiance: Proxy approach

- e.g. SFO (Chapman et al. 2012/2013); NRL (Coddington et al. 2016); EMPIRE (Yeo et al. 2017)
- Fitting indices of magnetic activity to measured TSI & SSI is an obvious & straightforward way to reconstruct solar irradiance but not without limitations.

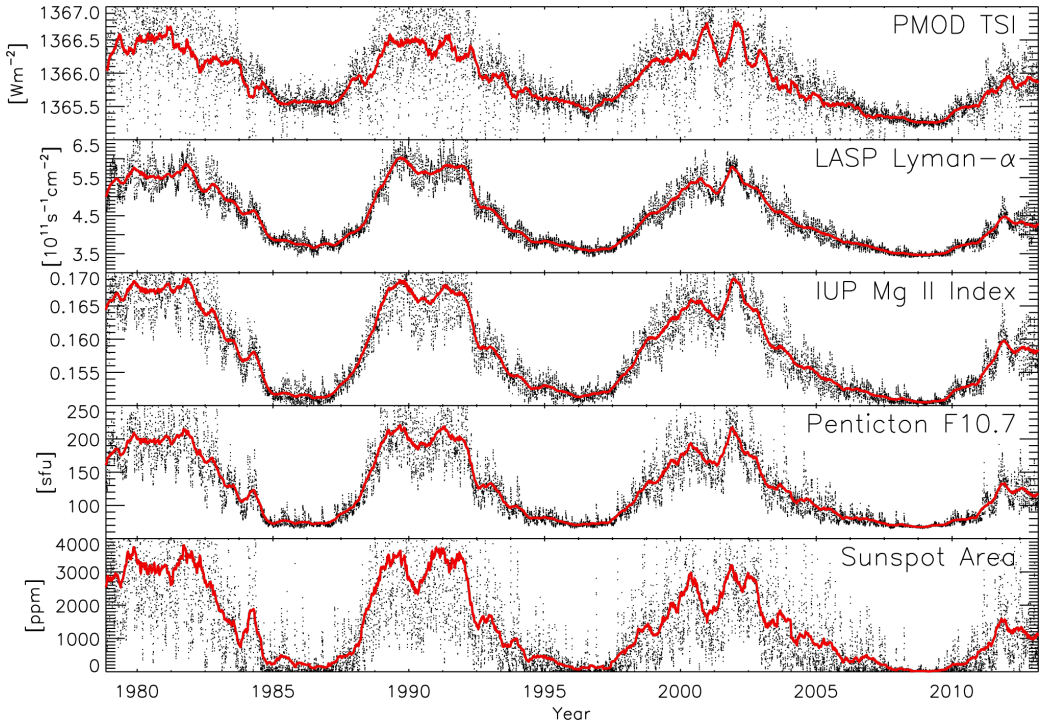


Figure 6: TSI and indices of solar magnetic activity.

Just because we could doesn't mean we should!

- Can the index formed at one height in the solar atmosphere represent radiation formed at other heights?
- Are activity indices and solar irradiance really linearly related?
- Affected by measurement uncertainty.
- Not possible at all wavelengths (limited reliable SSI measurements).

Modelling solar irradiance: Semi-empirical approach

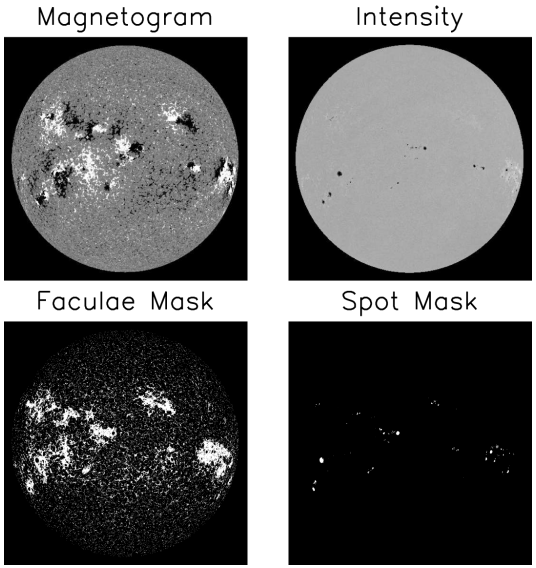
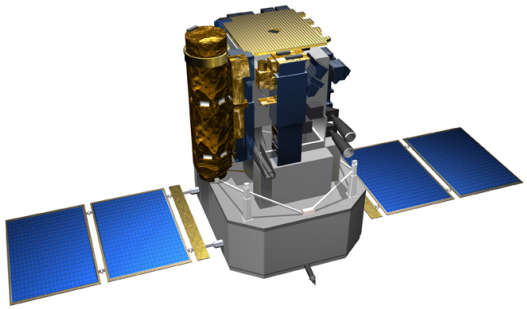


Figure 7: Identifying faculae & sunspots by the magnetogram signal & intensity.

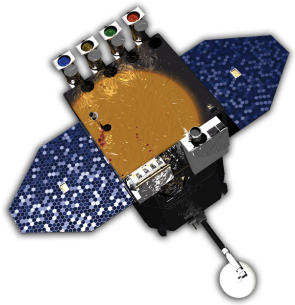
SATIRE-S (Krivova et al. 2003; Yeo et al. 2014)

- 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 (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 & UV to IR SSI spanning the entire period of satellite observation at daily cadence.

Can models reproduce measured TSI?

Proxy

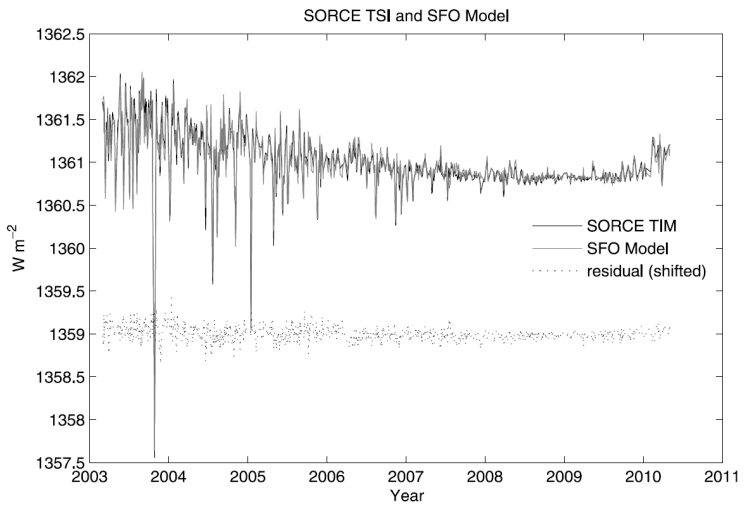


Figure 8: SFO TSI (Chapman 2012).

Semi-empirical

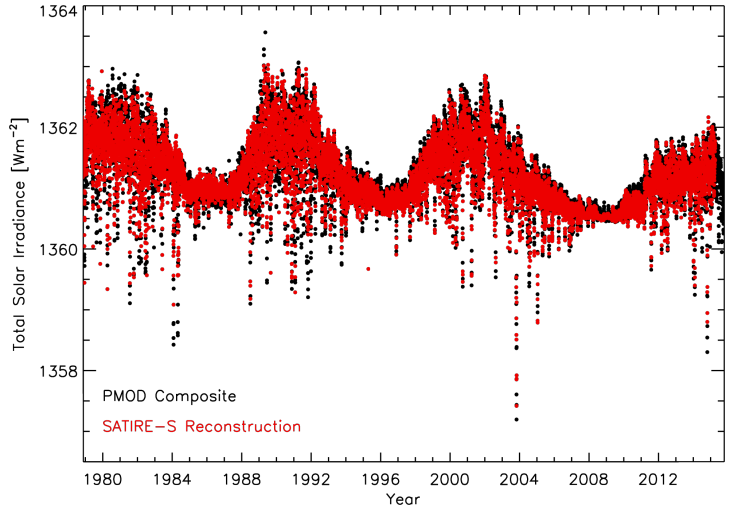


Figure 9: SATIRE-S TSI.

Issues persists at decadal timescales, but otherwise, models, proxy or semi-empirical, can recover $> 90\%$ of the variability in measured TSI.

Can models reproduce measured SSI?

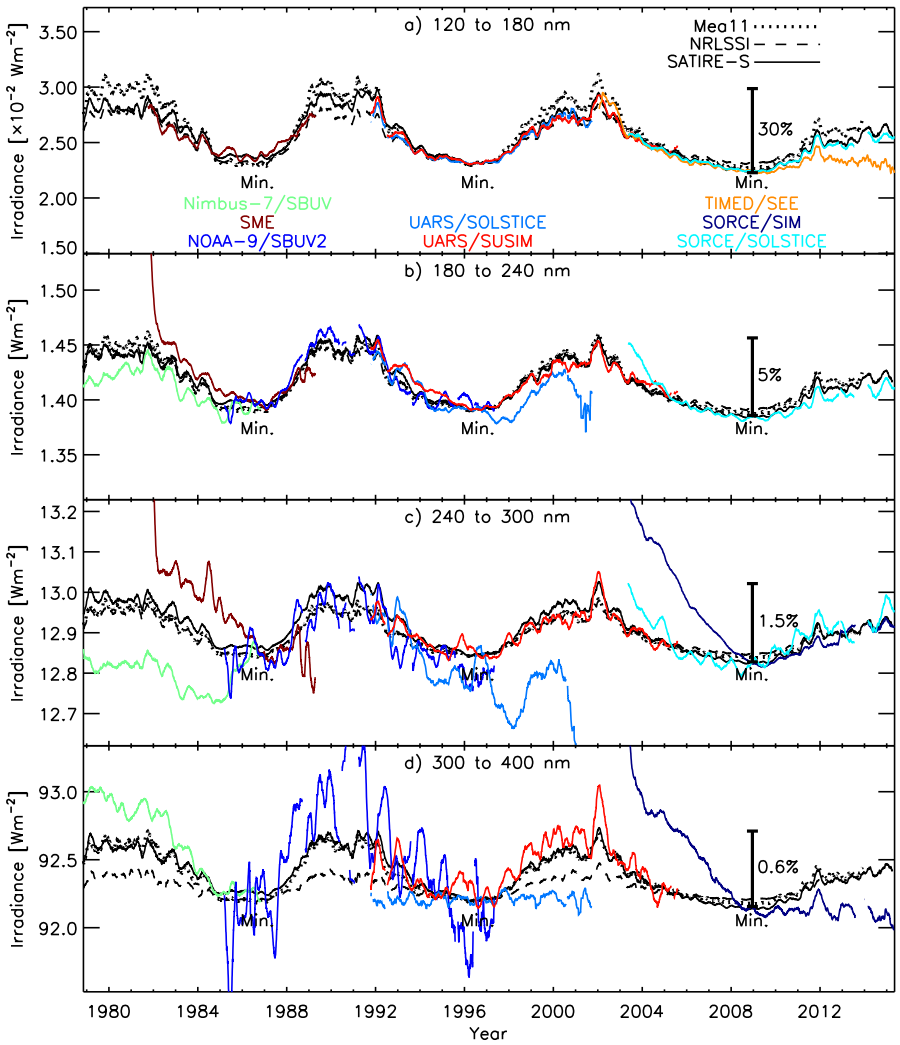


Figure 10: Measured (colour) and reconstructed (black) UV SSI (Yeo et al. 2015).

Agreement between the various records and reconstructions deteriorates with wavelength.

Can models reproduce measured SSI?

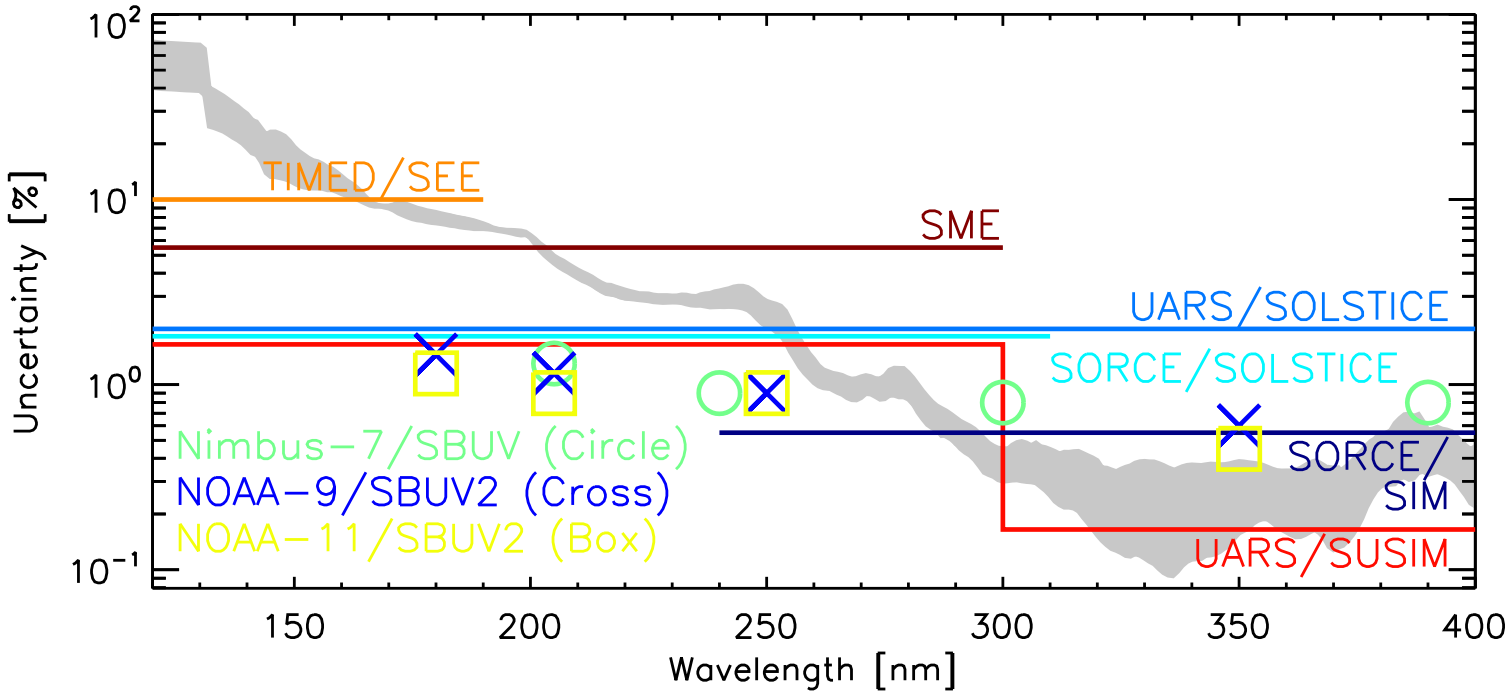
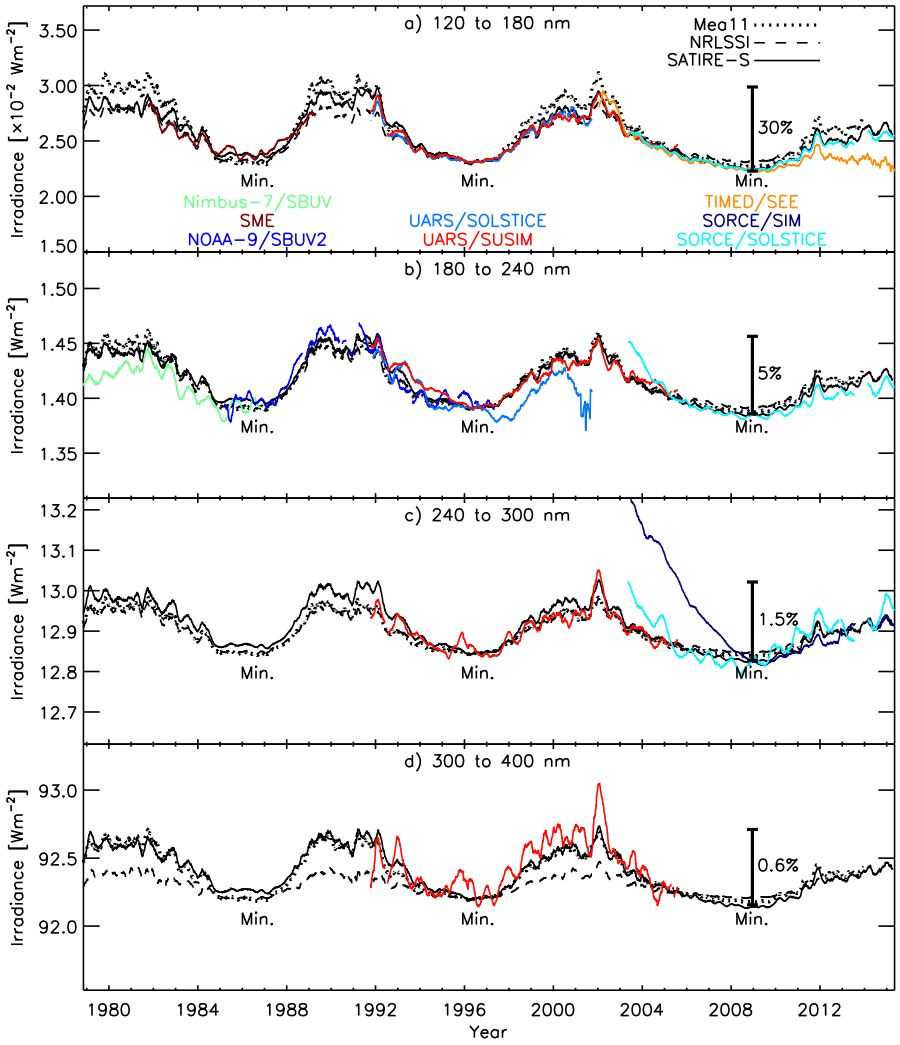


Figure 11: Long-term uncertainty in measurements (colour) and solar cycle amplitude in models (grey) (Yeo et al. 2015).

Solar cycle variability drops with wavelength. For certain instruments, solar cycle variability drops below the limits of measurement stability.

Can models reproduce measured 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 proxy models markedly weaker (c.f. Yeo et al 2017, JGR).

Figure 12: Measured (colour) and reconstructed (black) UV SSI.

Modelling solar irradiance: Are we getting it right?

Assumption

Solar irradiance variability is driven by solar surface magnetism.

How can we prove that?

Can solar irradiance models based on this assumption reproduce measurements?

Problem

Yes, but all models have to be calibrated to solar irradiance measurements.

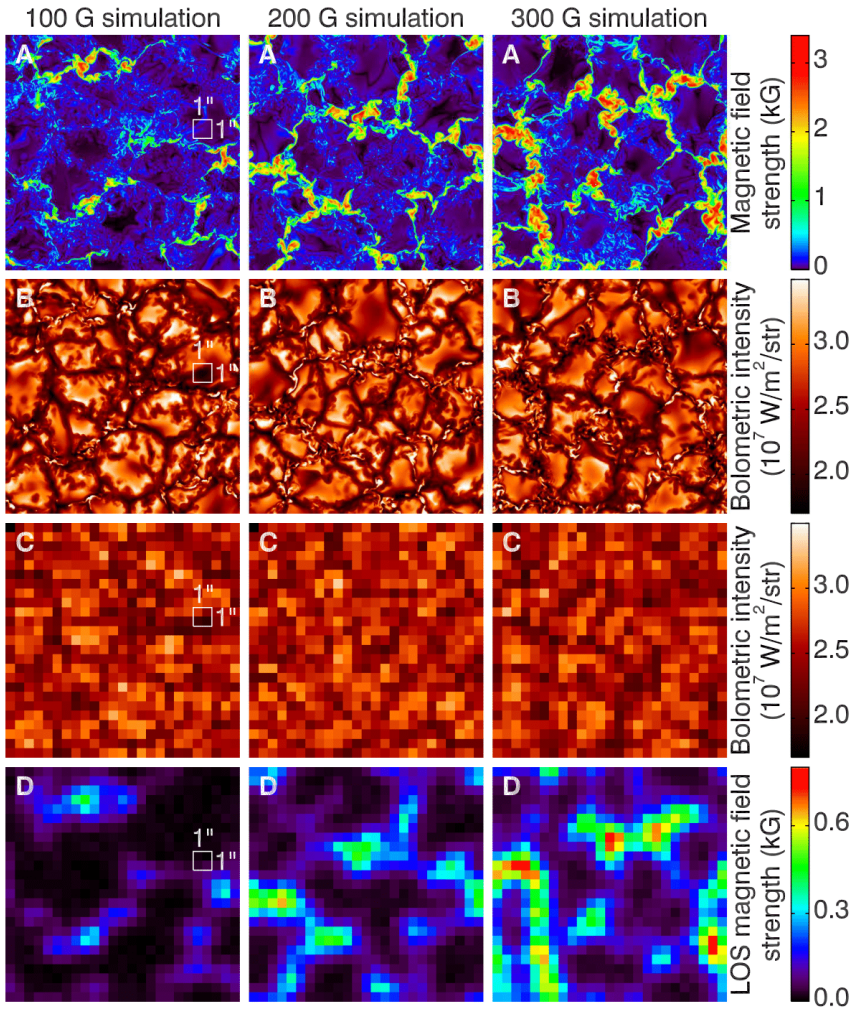
Why?

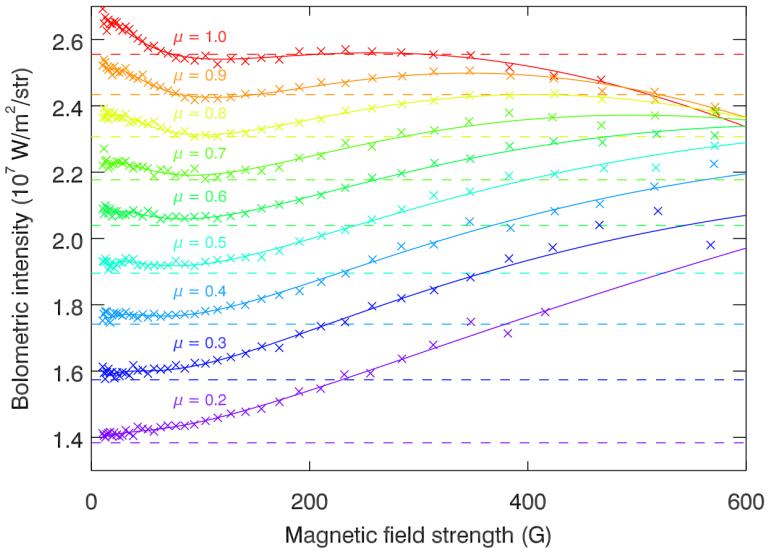
Due to limitations in solar observations, relationship between apparent magnetism & intensity not straightforward to derive without calibration.

Solution: SATIRE-3D (Yeo et al. 2017, PRL)

Magnetism-Intensity LUT based on HMI observations & MHD simulations.

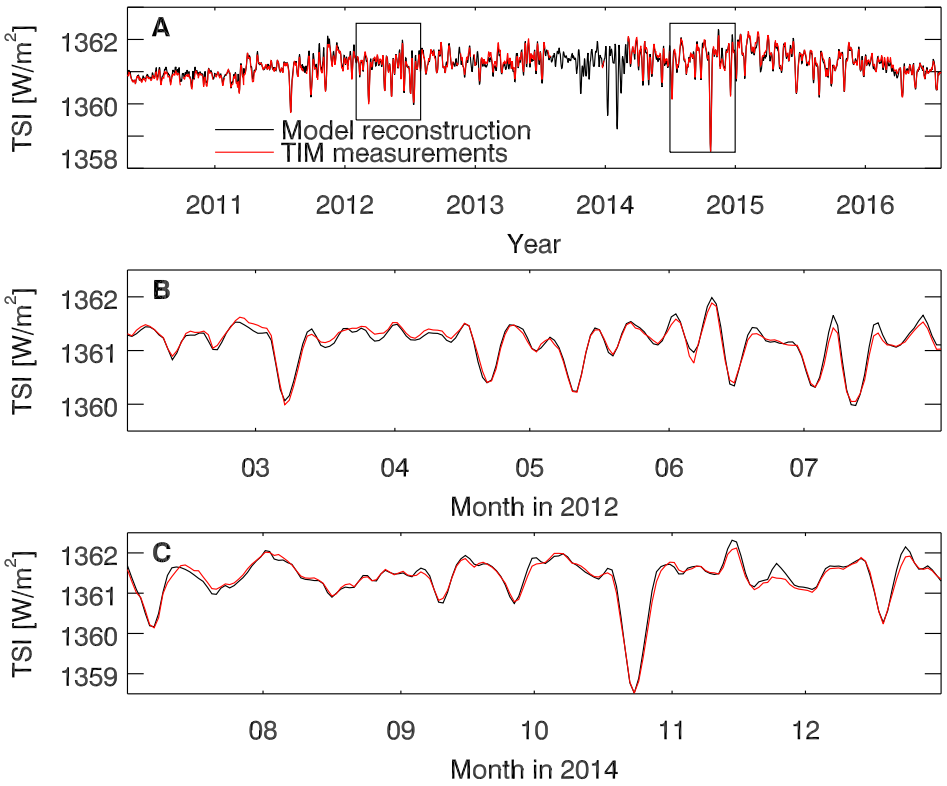
Modelling solar irradiance: Are we getting it right?





Emulating the HMI instrument with the MHD simulations allowed us to relate HMI measured magnetic field strength to intensity directly.

Modelling solar irradiance: Are we getting it right?



With this advance, SATIRE-3D is the only model to reproduce measurements while not requiring any calibration to the latter.

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Solution: SATIRE-3D (Yeo et al. 2017)

Only model to reproduce measurements while not requiring any such calibration.

Summary

- TSI & SSI variability are natural drivers of climate change.
- TSI & UV SSI monitored since 1978, revealing correlation to the solar cycle, suggesting a link to solar magnetism.
- TSI & SSI variability modelled as consequence of solar surface magnetism either empirically (e.g. NRL & EMPIRE) or physically (e.g. SATIRE).
- Models largely successful in replicating measurements, but in requiring calibration to the latter, do not prove the link between solar irradiance and magnetism.
- SATIRE-3D, making use of state-of-the-art observations from HMI and MHD simulations, require no such calibration, confirming the link between solar irradiance and magnetism.