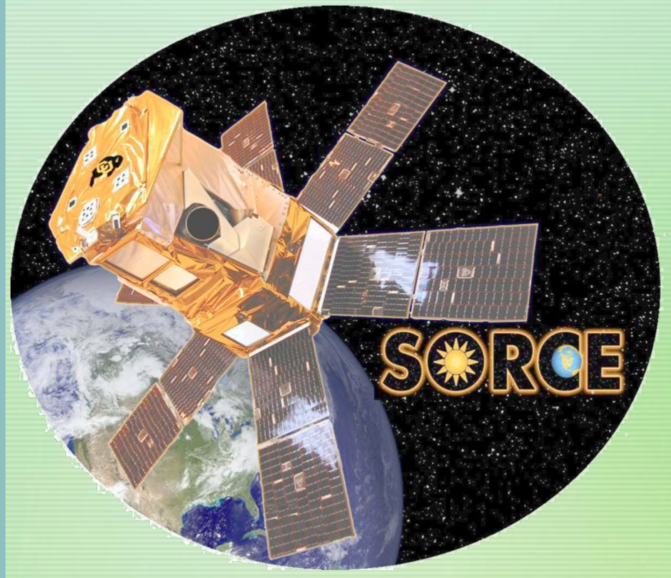
Solar Variability Results from the SORCE and TSIS-1 Missions



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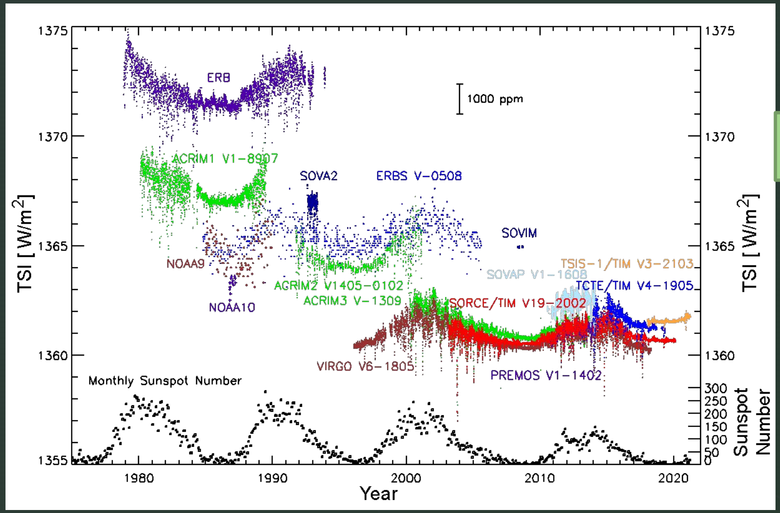
Talk Summary

Summary

- Introduction to the Solar Irradiance Climate Records
  - Satellite-era Record over 4 decades (27-day rotations, 11-year / 22-year cycles)
  - Solar-proxy Record over 4 centuries (Maunder Minimum, 100-year Gleissberg cycle)
  - Long-term Ice-core and Tree-ring Records over many centuries (Grand Min. & Max.)
- Solar Rotational (27-day) Variability
  - Ultraviolet (UV) and Total Solar Irradiance (TSI) are in-phase 86% of the time
- Solar Cycle (11-year) Variability
  - SORCE solar cycle variability results are most accurate for $\lambda < 300$ nm
  - TSIS-1 provides improved solar variability results, especially important for infrared (IR)
- Comparison of Recent 2019-2020 Minimum to Previous 2008-2009 Minimum
  - There is no significant (if any) change in the irradiance between these minima
- REFERENCE: Woods et al., *Solar Phys*, 2022, https://doi.org/10.1007/s11207-022-01980-z

Satellite-era Record

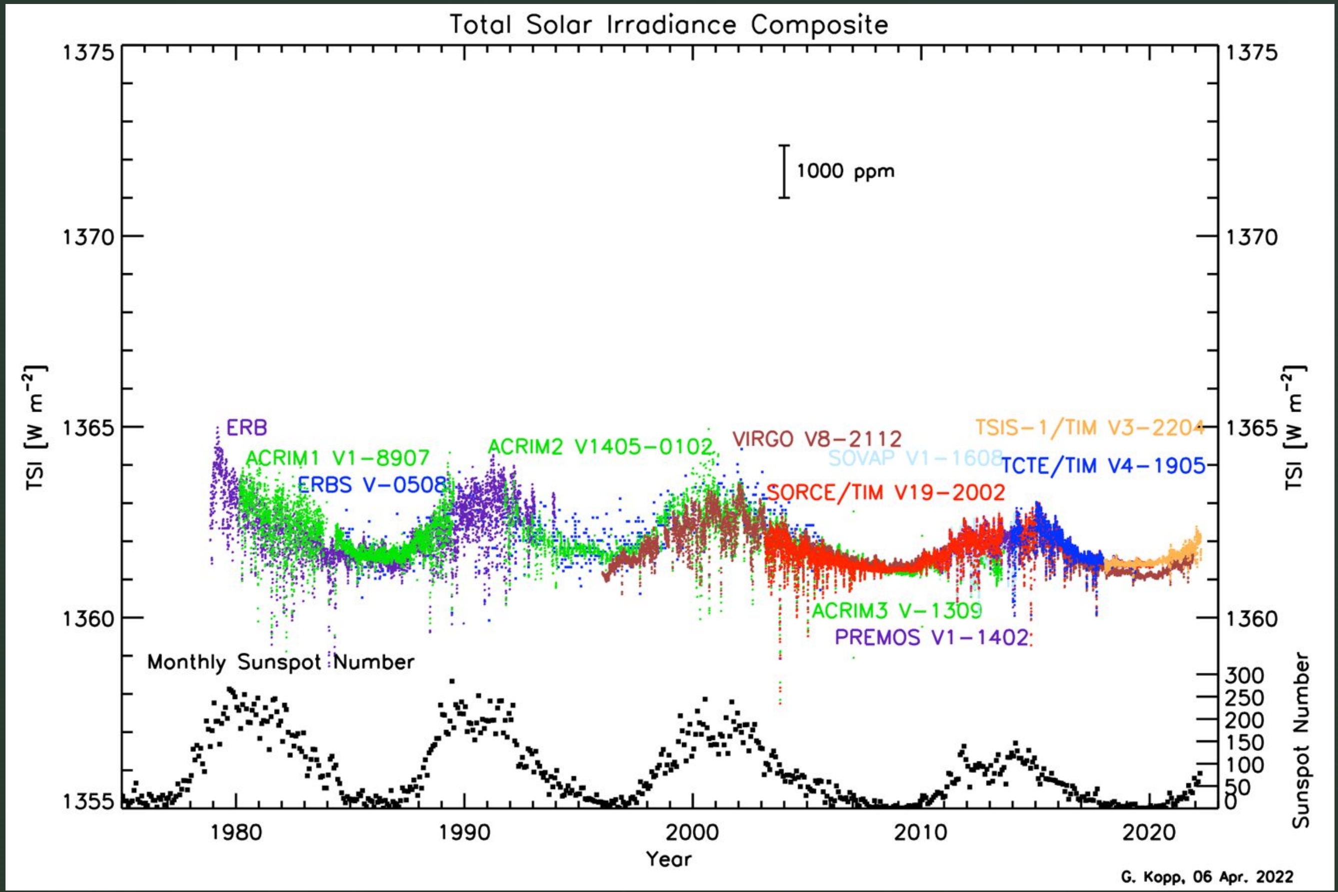
Total Solar Irradiance (TSI) Climate Record



17 TSI data sets make up the TSI Climate Record.

The 4-decade TSI Climate Record accurately defines variability for the approx. 27-day solar rotations and for the 11-year solar activity cycle (Schwabe cycle).

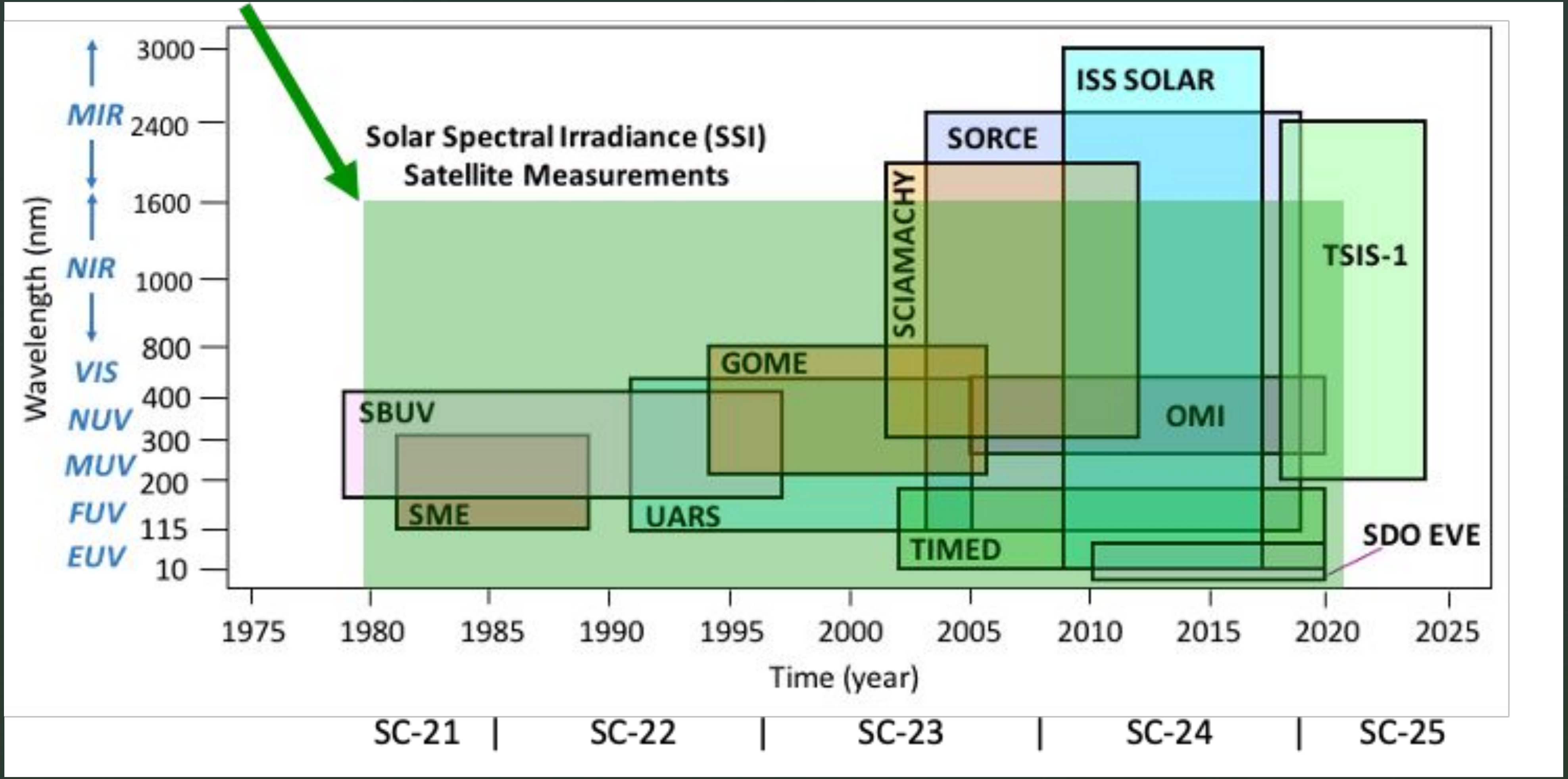
The 11-year cycle is driven by solar 22-year solar magnetic cycle (Hale cycle).



Figures from G. Kopp
https://spot.colorado.edu/~koppg/TSI/

Solar Spectral Irradiance (SSI) Climate Record

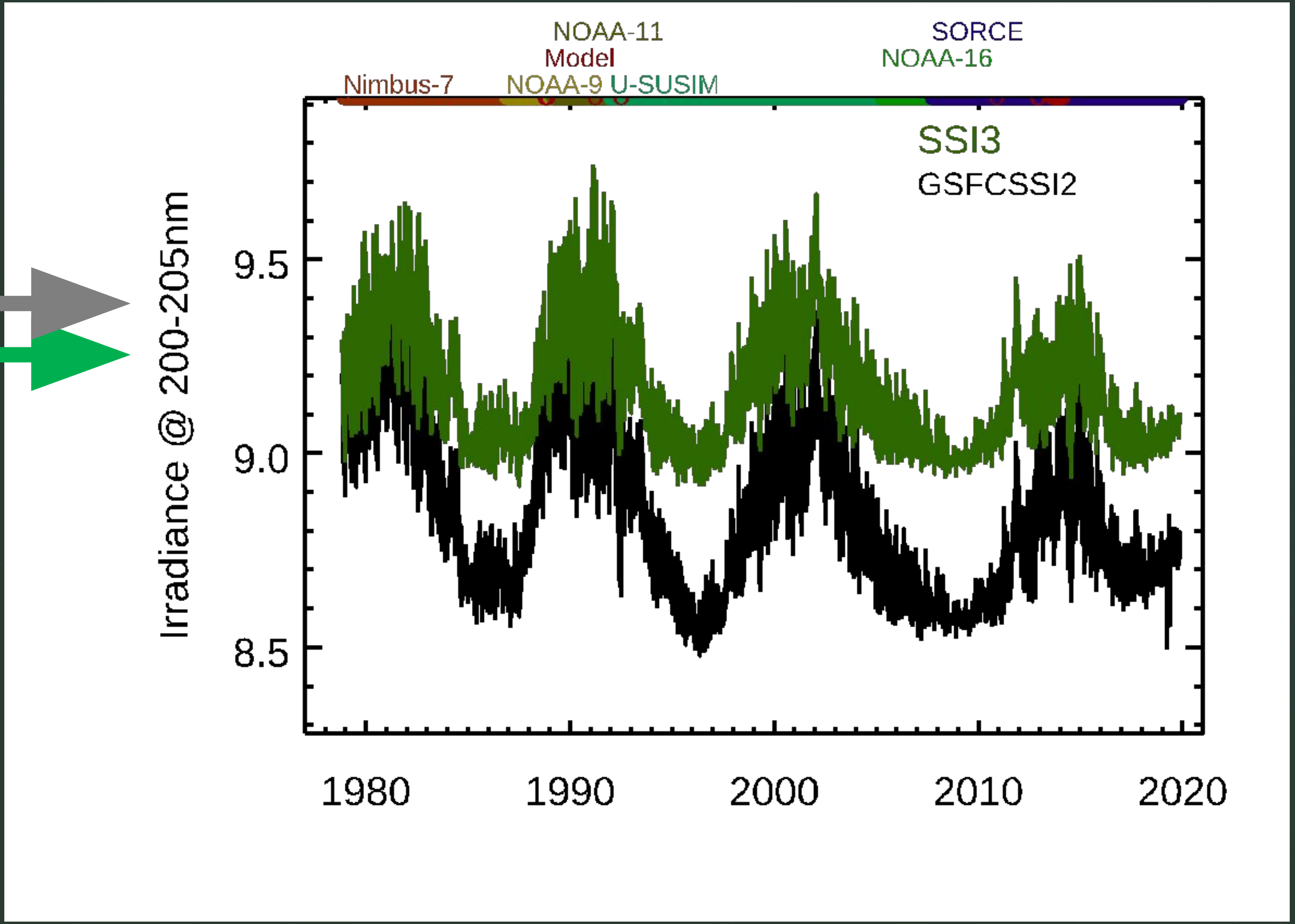
- 11 SSI data sets are used for the SSI Climate Record.
- There are many spectral and temporal gaps though for the SSI observations.
- Solar SSI models are important to fill the gaps in wavelength and time.



Solar Spectral Irradiance (SSI) Records

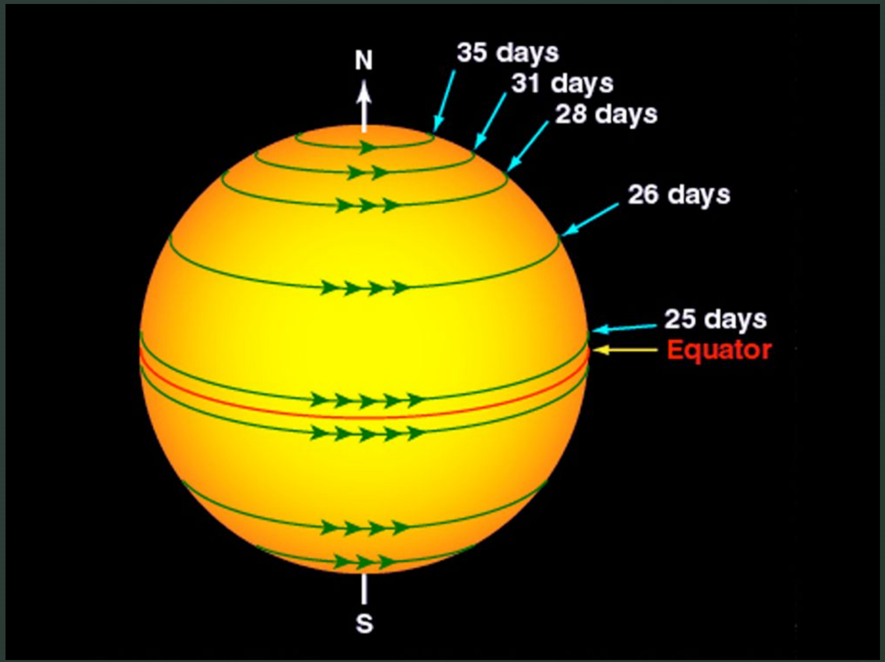
Solar SSI Composites
SIMc – Mauceri et al. 2020
SOLID – Haberreitter et al. 2017
SSI-2 – DeLand et al. 2019
SSI-3 – Woods & DeLand 2021

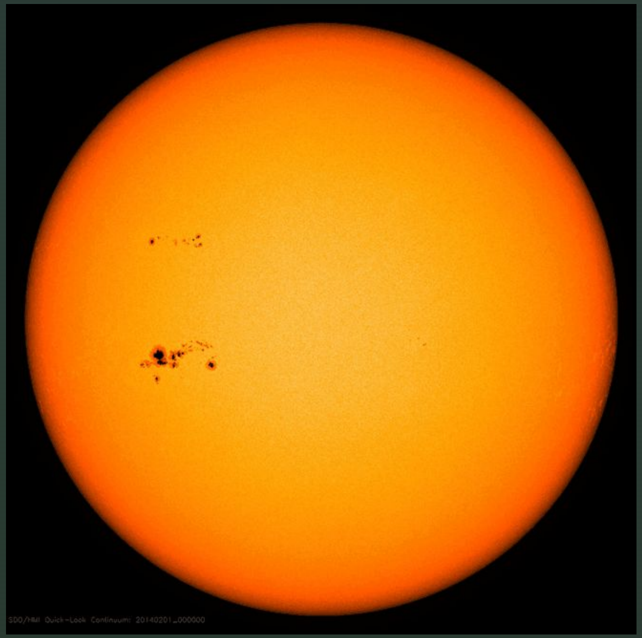
Solar SSI Variability Models
NRLSSI-3 – Lean, Coddington
SATIRE-S – Krivova et al. 2011
SRPM – Fontenla et al. 2011



SORCE SSI observations are critical part of the SSI records.
Figure 8 in Woods and DeLand, *Earth & Space Sci.*, 2021

NRLSSI-2 solar model has been adopted as NOAA SSI Climate Record (Coddington et al., 2016).

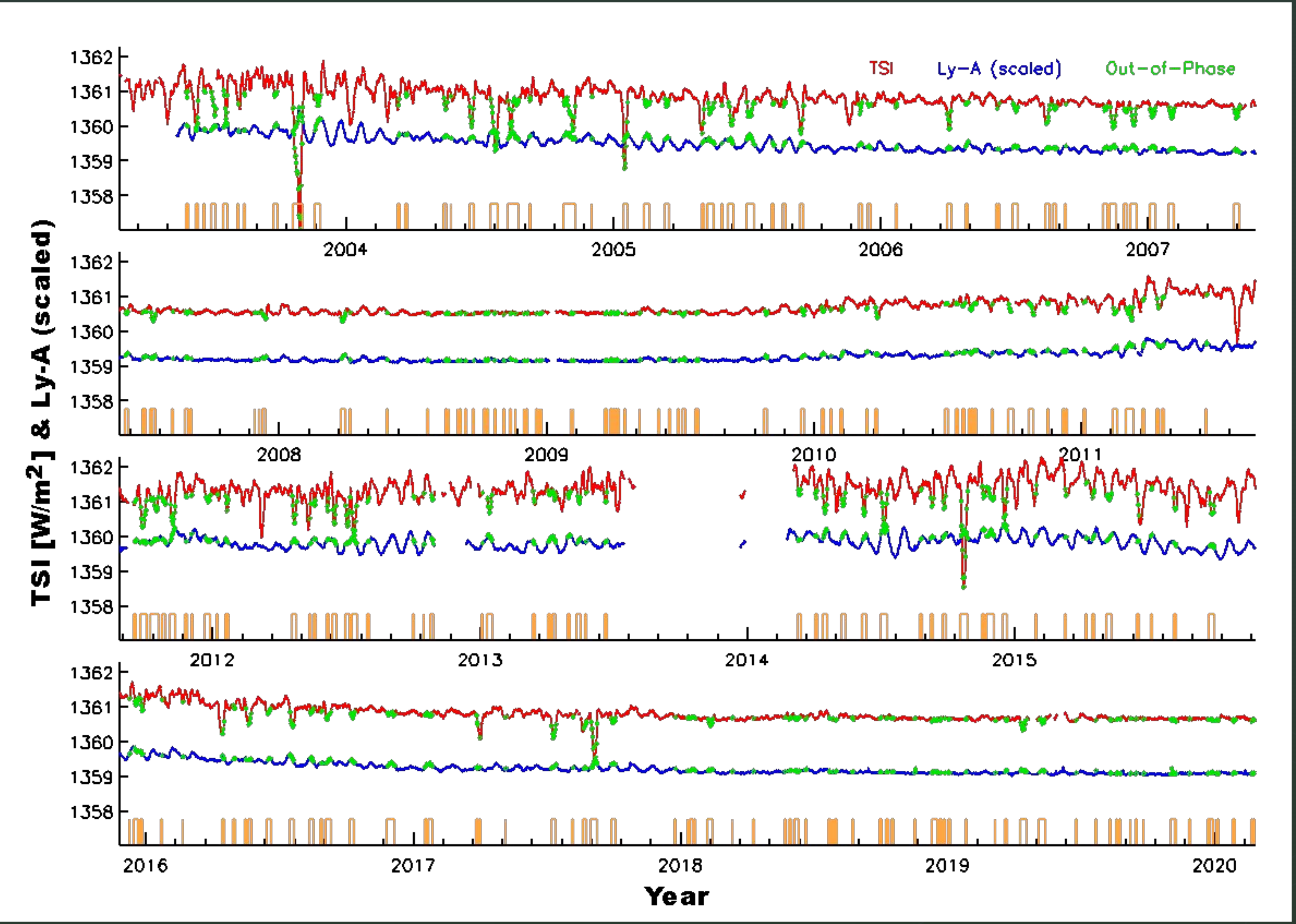




Solar Rotational Variability: ~27-days

Ultraviolet Ly-α and TSI are in-phase 86% of the time

(there are 205 solar-rotation periods over the 17-year SORCE mission)



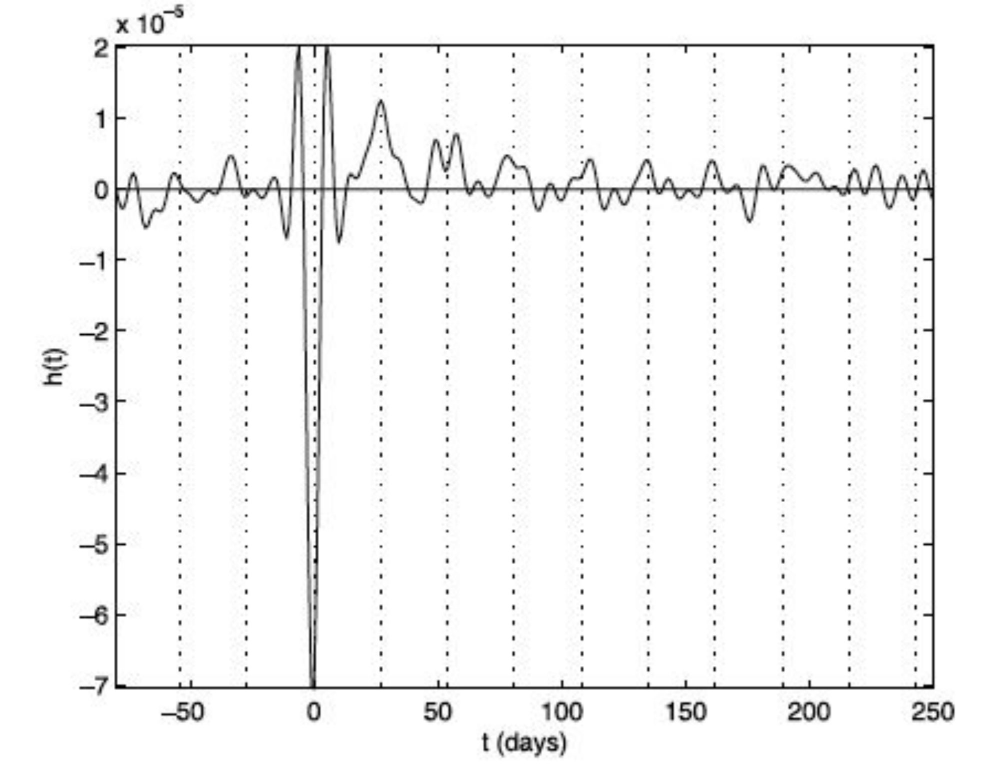
Out-of-Phase periods (green) are only 14% of the time !

Figure 9 in Woods et al., *Solar Phys.*, 2022

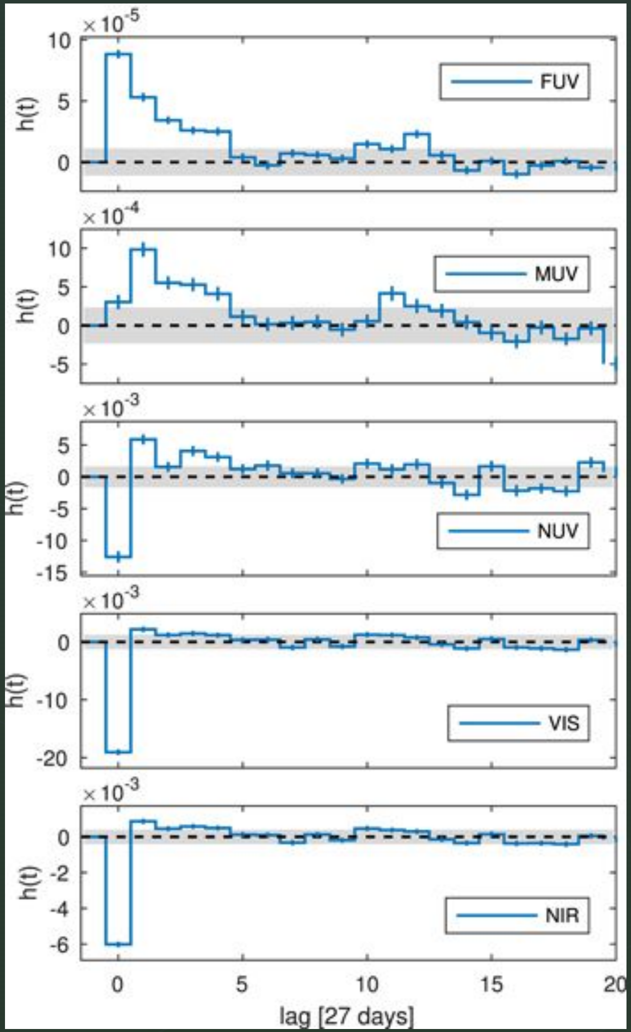
LASP

Ultraviolet Ly-α and TSI being in-phase 86% of the time is related to the Impulse Response Function for new Sunspots

Sunspot Impulse Response Function for TSI
(Preminger & Walton, *GRL*, 2005)
First Rotation: strong negative effect on TSI
Other Rotations: weak positive effect on TSI

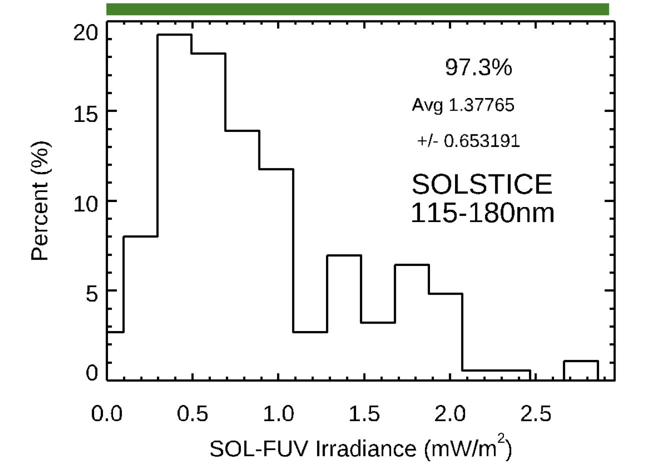


Sunspot Impulse Response Function for SSI
(Dudok de Wit et al., *Ap J*, 2018)

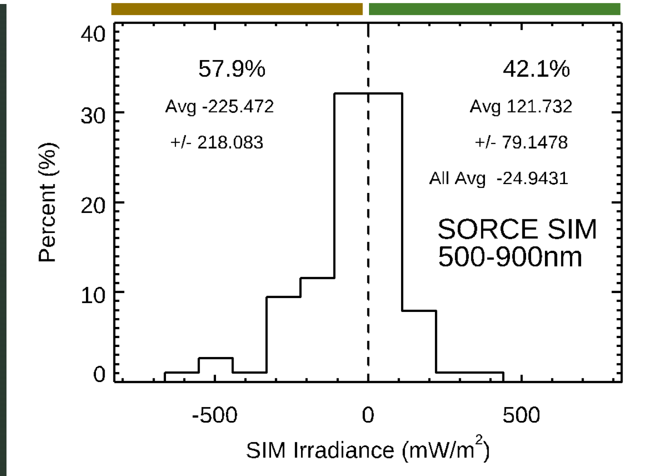


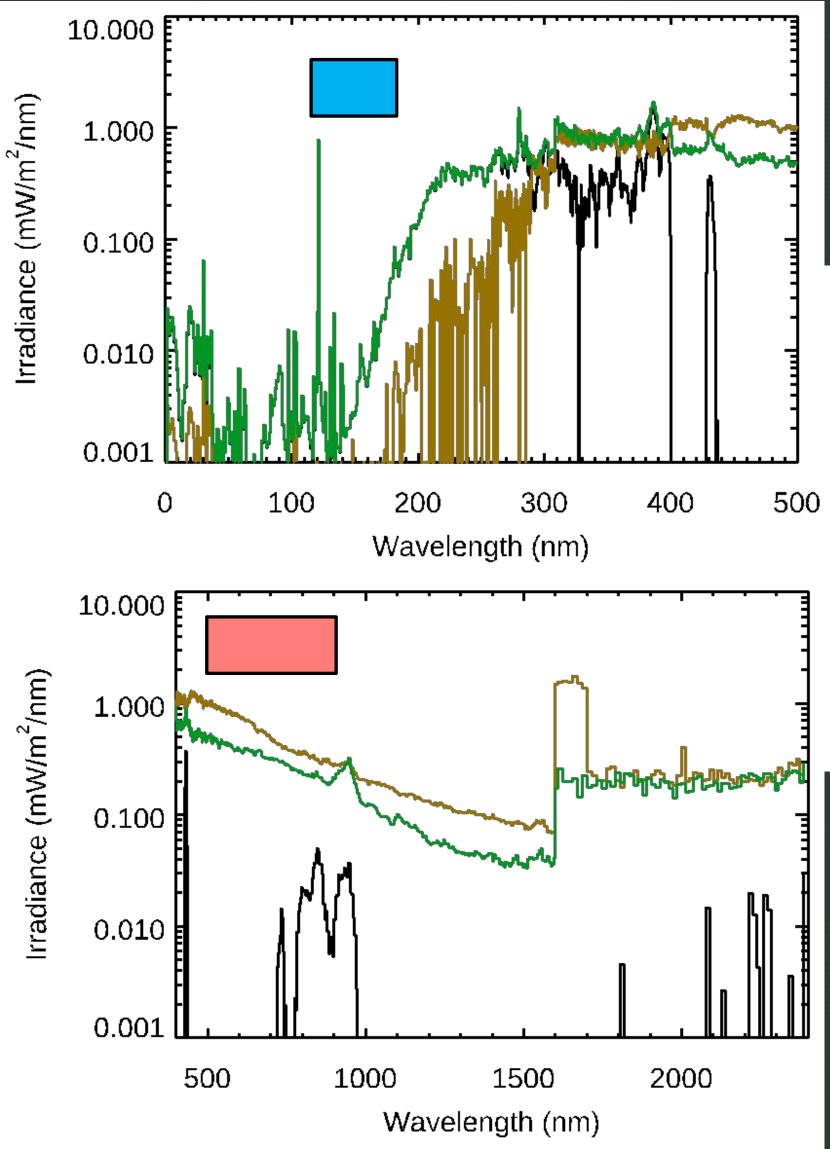
Phasing Relative to Ly-α: UV (λ< 290 nm) is in-phase and out-of-phase rotations are important for other λs

Positive-Only Rotational Variability



Positive & Negative Rotational Variability



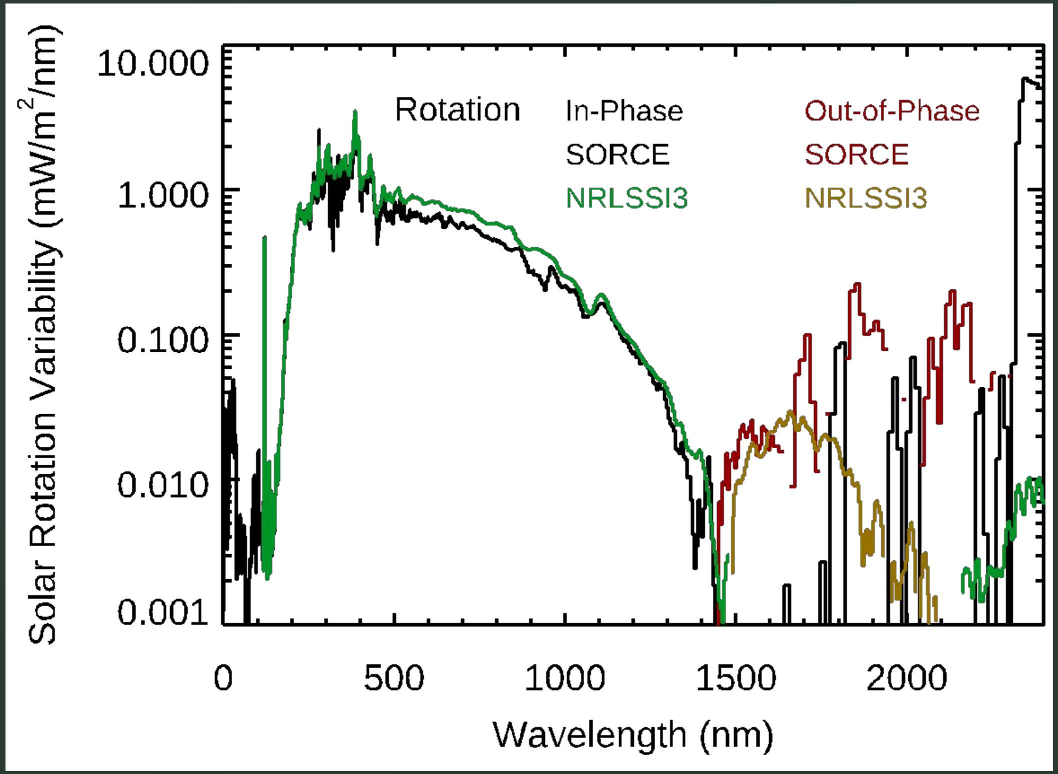


In-Phase (Positive)
Out-of-Phase (Negative)

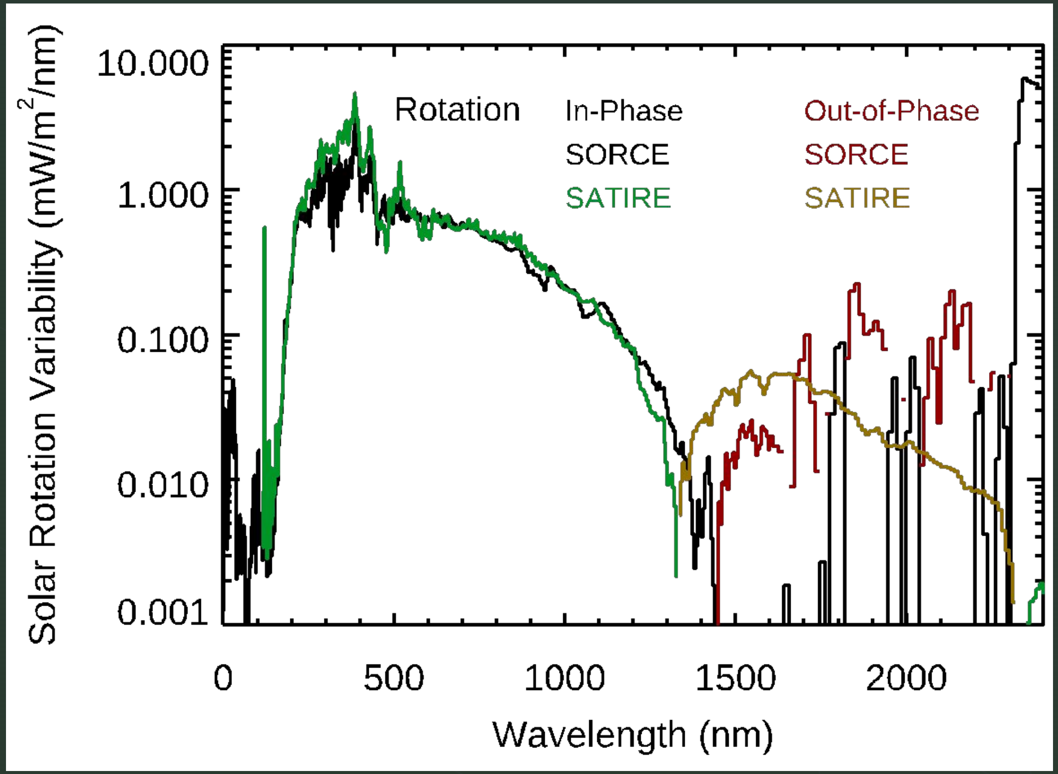
Black in right plot is the average variability for 205 rotation.
Figures 10 & 11 in Woods et al., *Solar Phys.*, 2022

NRLSSI-3 and SATIRE-S models agree even better with SORCE solar rotational variability for λ < 1600 nm

NRLSSI-3

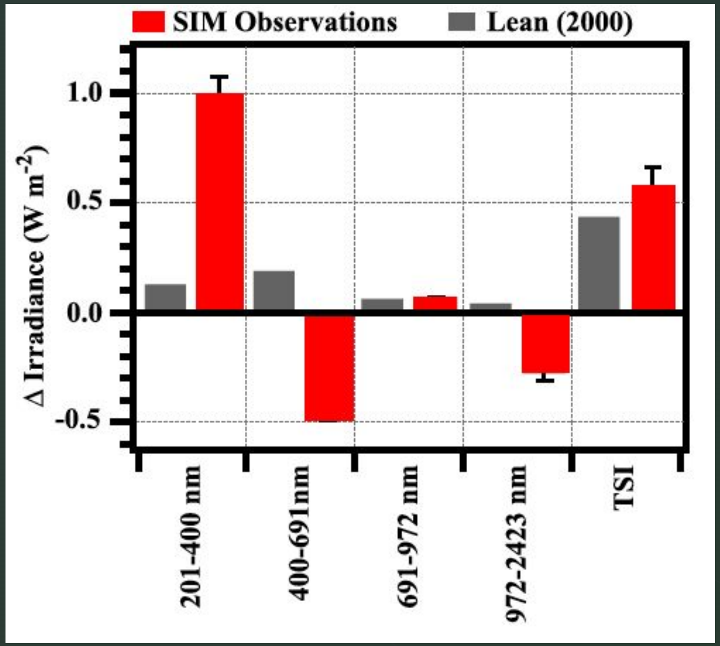


SATIRE-S

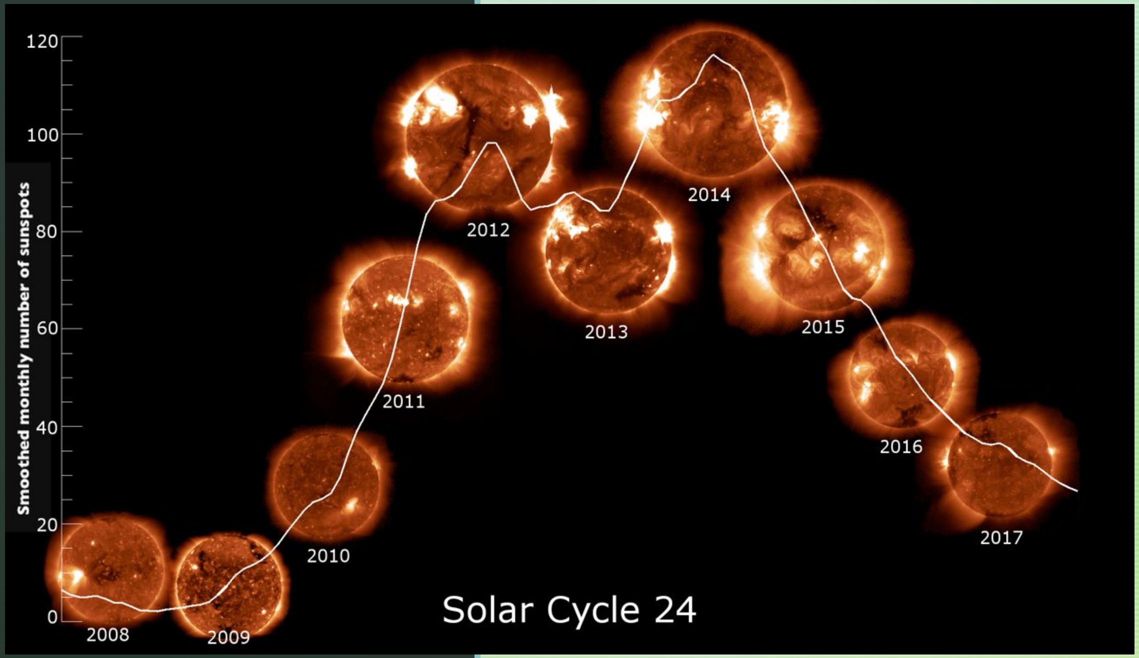


Biggest differences are in the near infrared (NIR).

Figure 13 in Woods et al., *Solar Phys.*, 2022

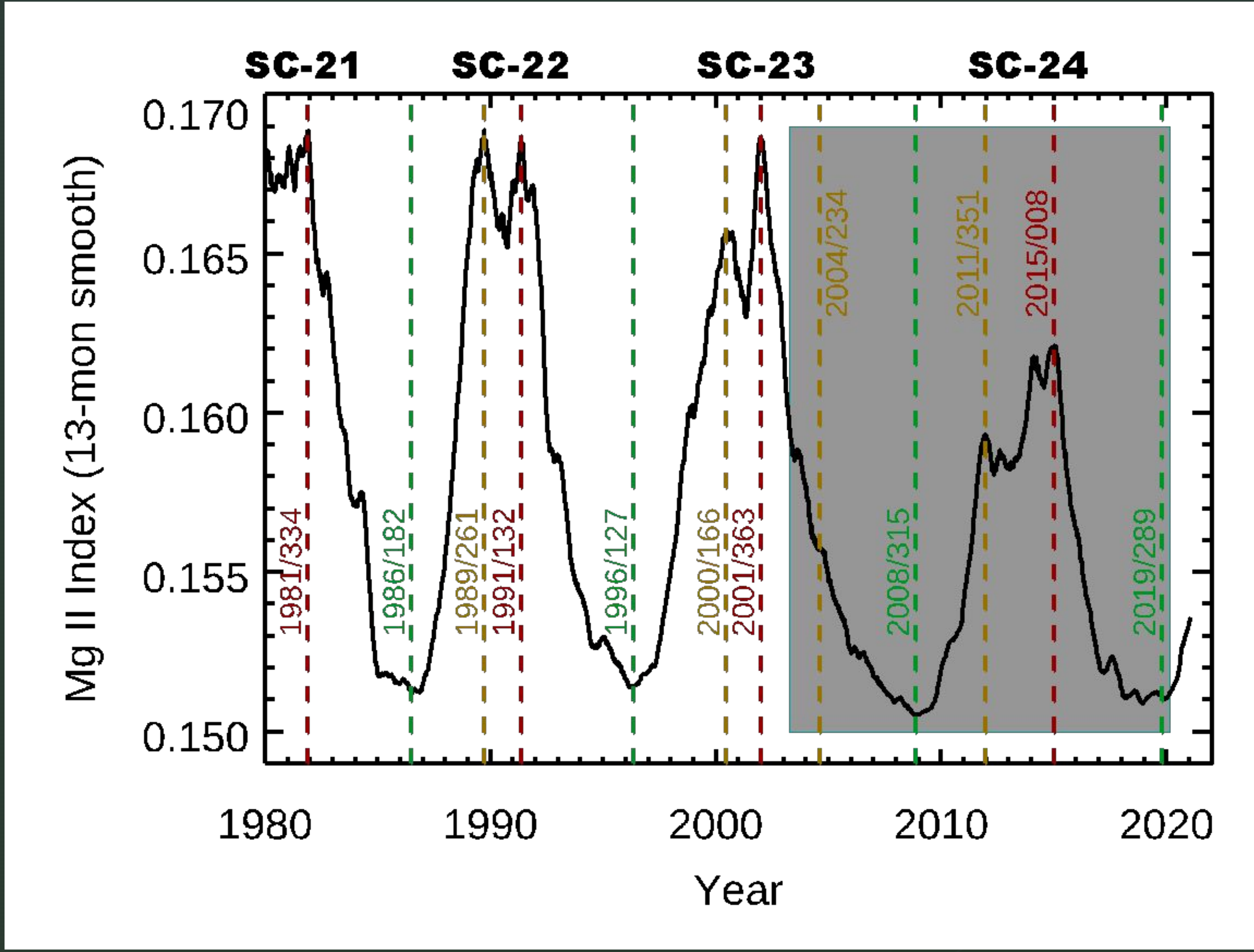


Harder et al. (2008)
SC-23 Result



Solar Cycle Variability: ~11-years

SORCE observed during the declining phase of Solar Cycle 23 and over all of Solar Cycle 24



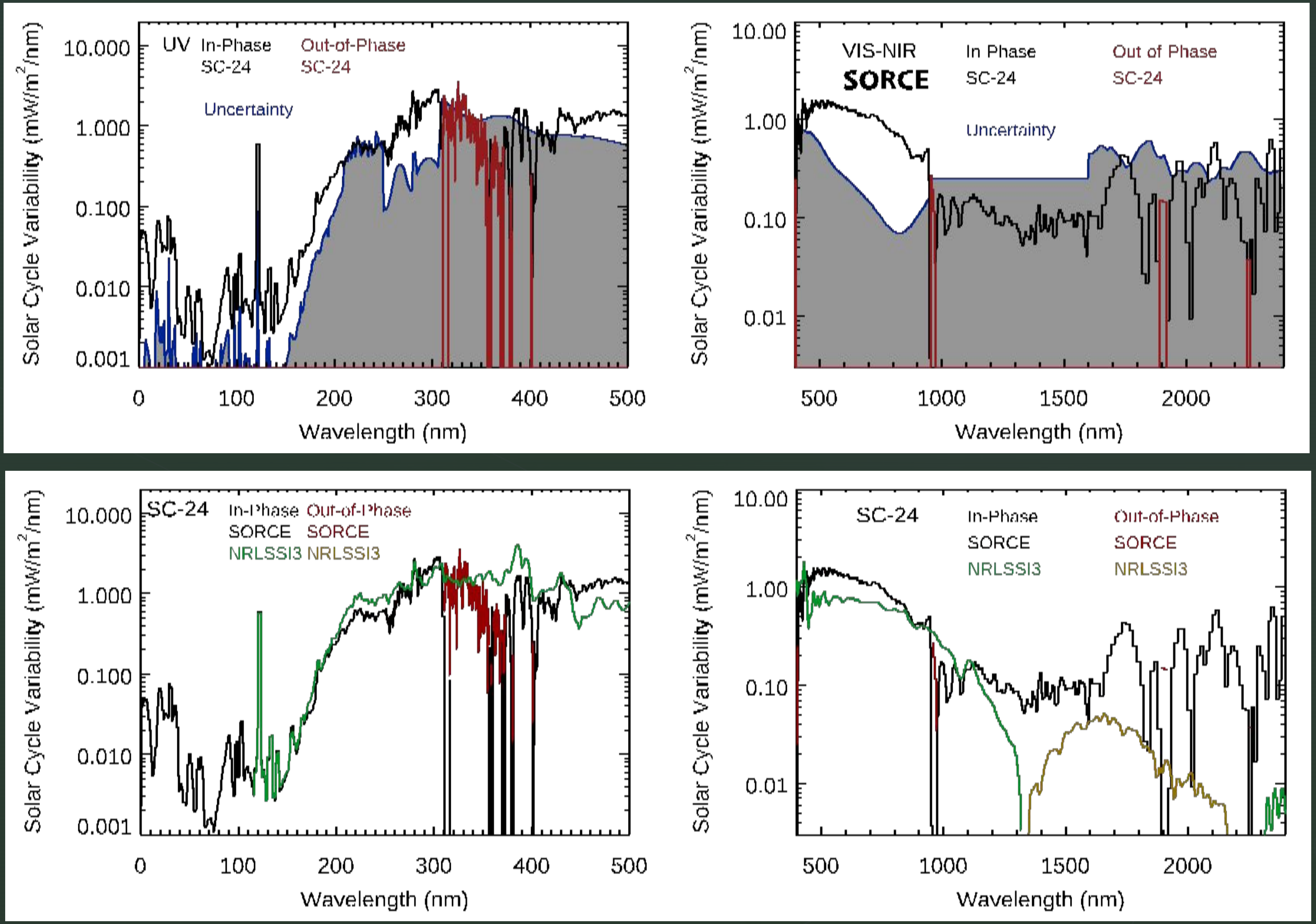
Best results are for Solar Cycle 24 using 2011 and 2008.

Figure 2 in Woods et al., *Solar Phys.*, 2022

Energy Variability (W/m²/nm) peaks at 300-500 nm. SORCE challenges are 308-430 nm and NIR > 900nm.

SORCE Energy Variability (Max-Min) W/m²/nm

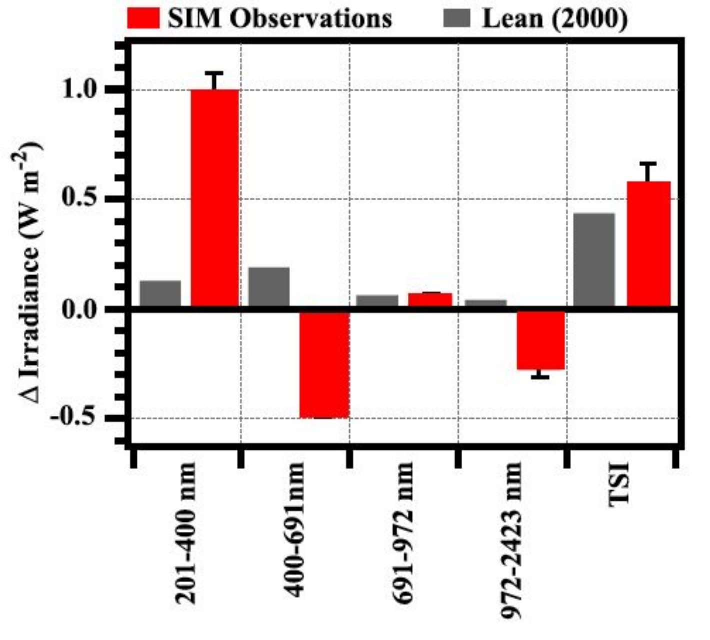
SORCE vs. NRLSSI-3



SIM results at 308-430nm and λ>900nm are only 1-σ results.
Figures 3 & 4 in Woods et al., *Solar Phys.*, 2022

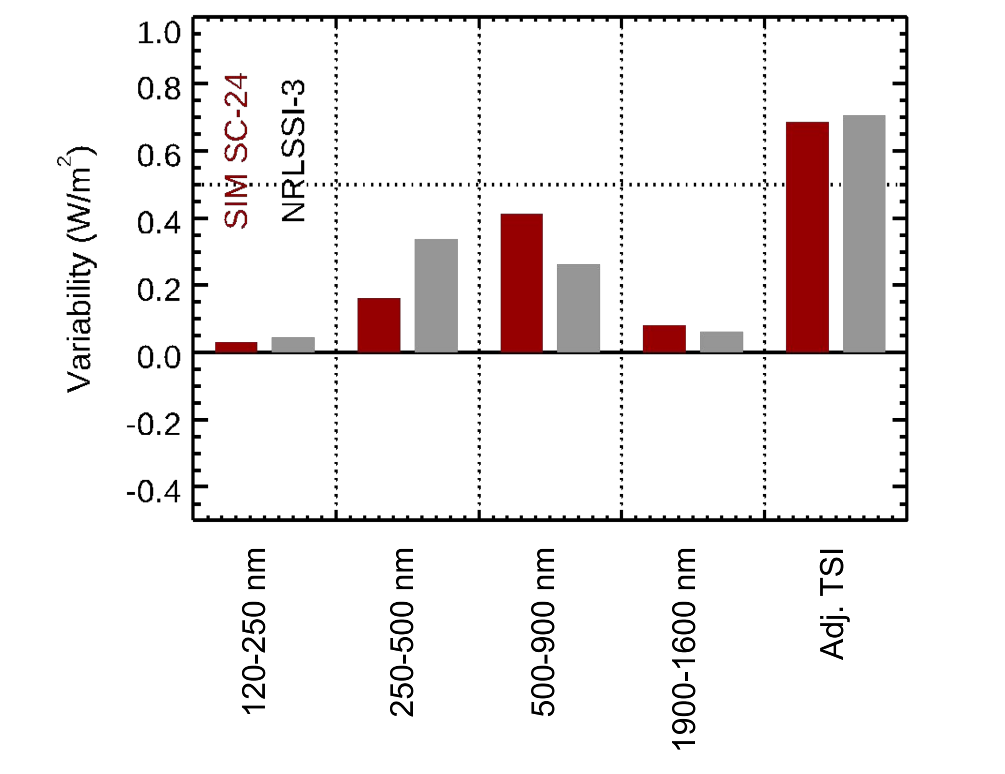
NRLSSI-3 and SORCE variability is more consistent in broad bands for Solar Cycle 24

- SORCE SIM SC-23 Result



Harder et al. (2008)

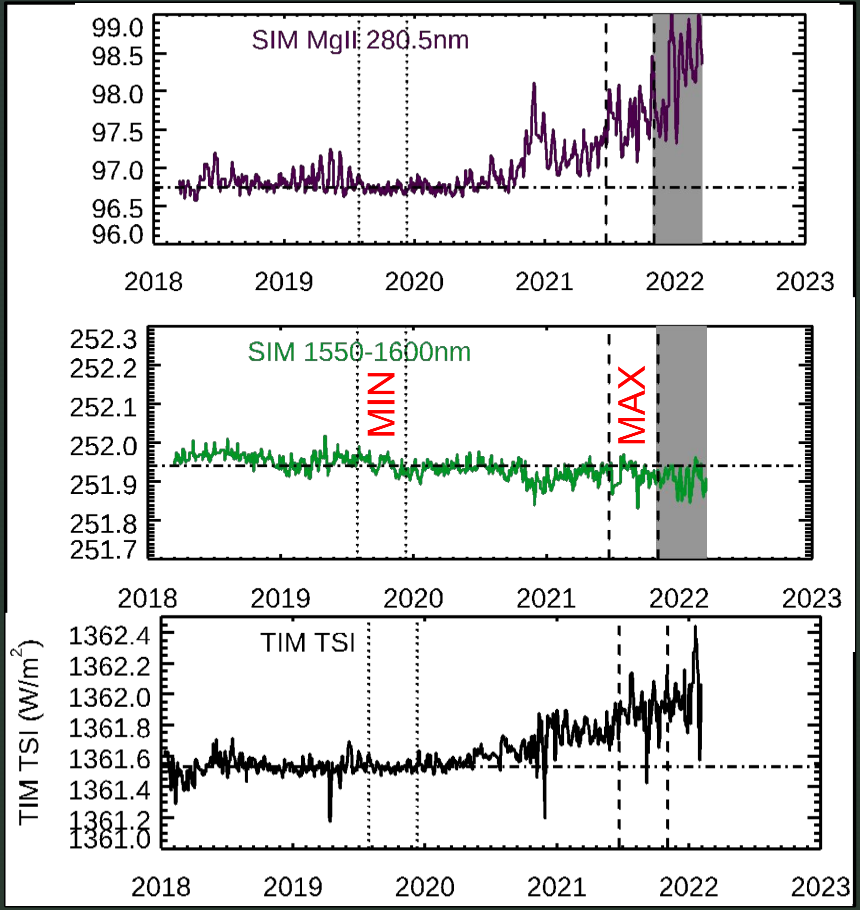
SORCE SIM SC-24 Result

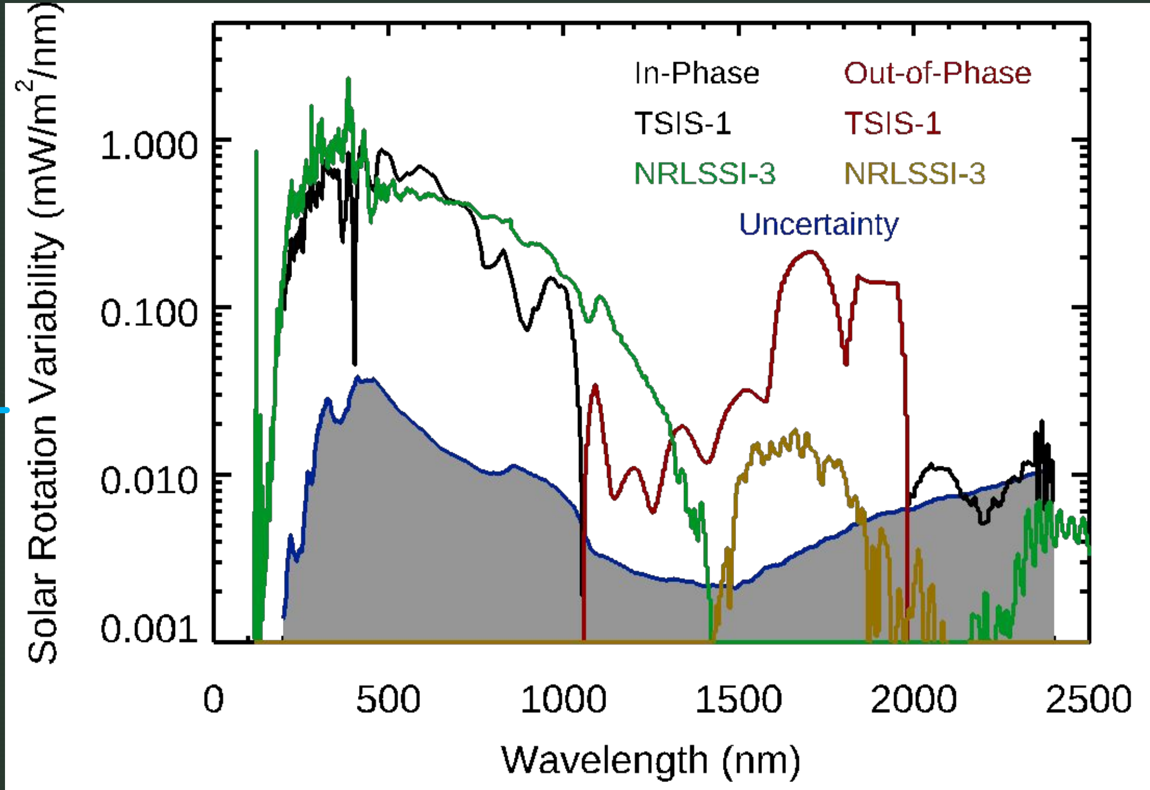


Woods et al. (2022)

TSIS-1 Solar Cycle 25 Variability

- Second and third generation SIM instruments aboard TSIS-1 and CSIM have much improved accuracy and measurement precision than first-generation SORCE/SIM.
- Recent increases in solar activity are providing improved variability results.
  - The NIR variability is notably more accurate and shows interesting differences to NRLSSI-3.
  - New results are considered preliminary due to last SIM-3 calibration being in Oct. 2021.





TSIS-1 SIM solar cycle variability result indicates more out-of-phase variability for longer than 1000 nm.

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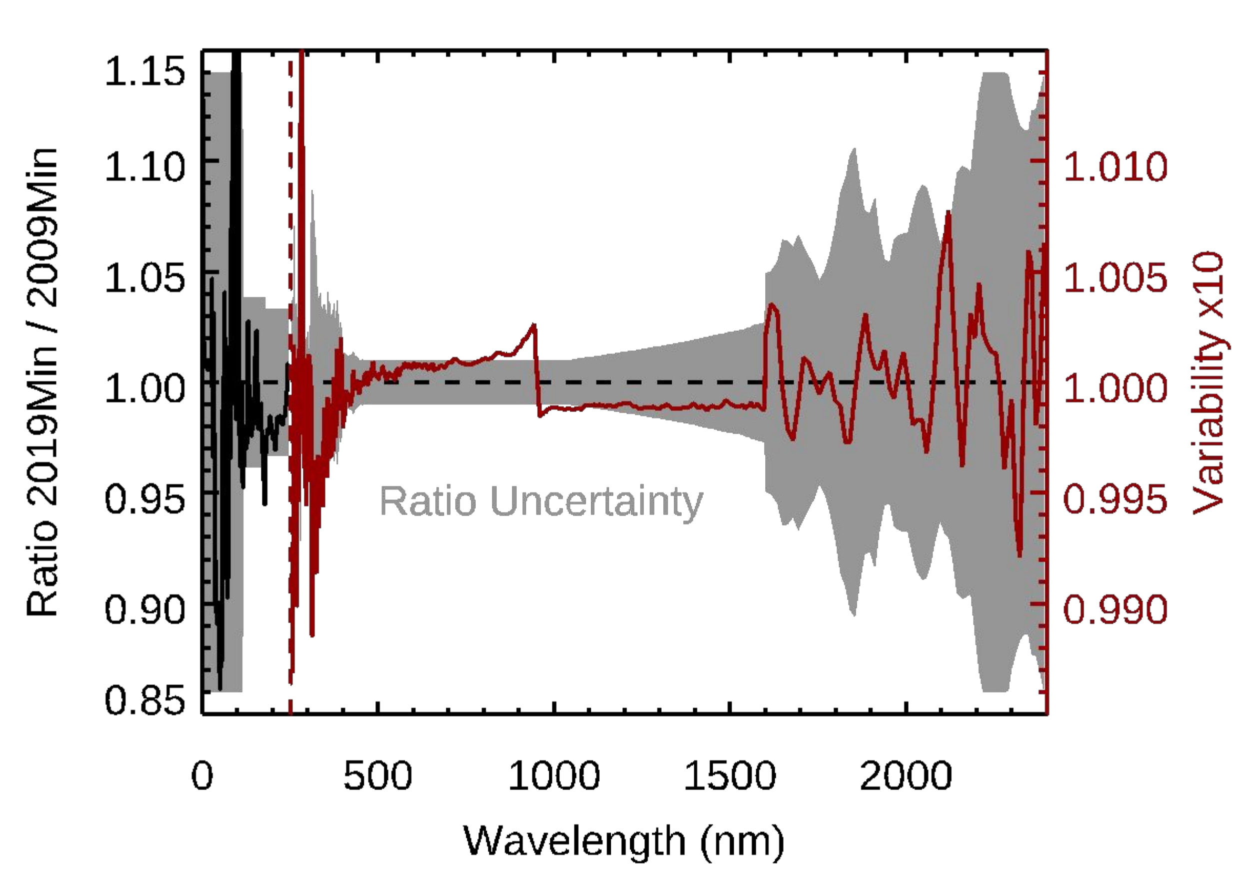
Summary

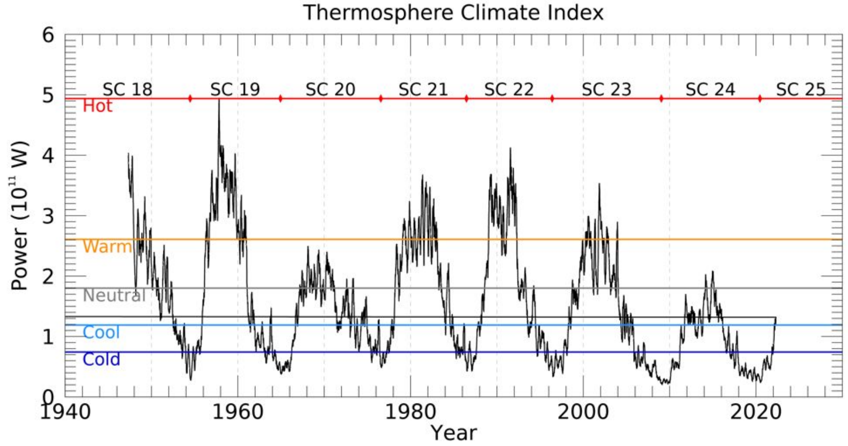
Extra Slides

Solar Minima Comparison of 2019-2020 to 2008-2009. Conclude that there is no change larger than 1-σ uncertainty.



Solar VUV (0-200nm) appears to be 2% lower in 2019-2020 than 2008-2009.

SABER data indicate similar thermosphere climate index for this recent minimum as in 2008-2009.



SORCE/SIM Integrated SSI change is -0.05 W/m^2 (± 2.8 W/m^2) lower in 2019-2020.
SORCE/TIM TSI change is +0.14 W/m^2 (± 0.14 W/m^2) higher in 2019-2020.

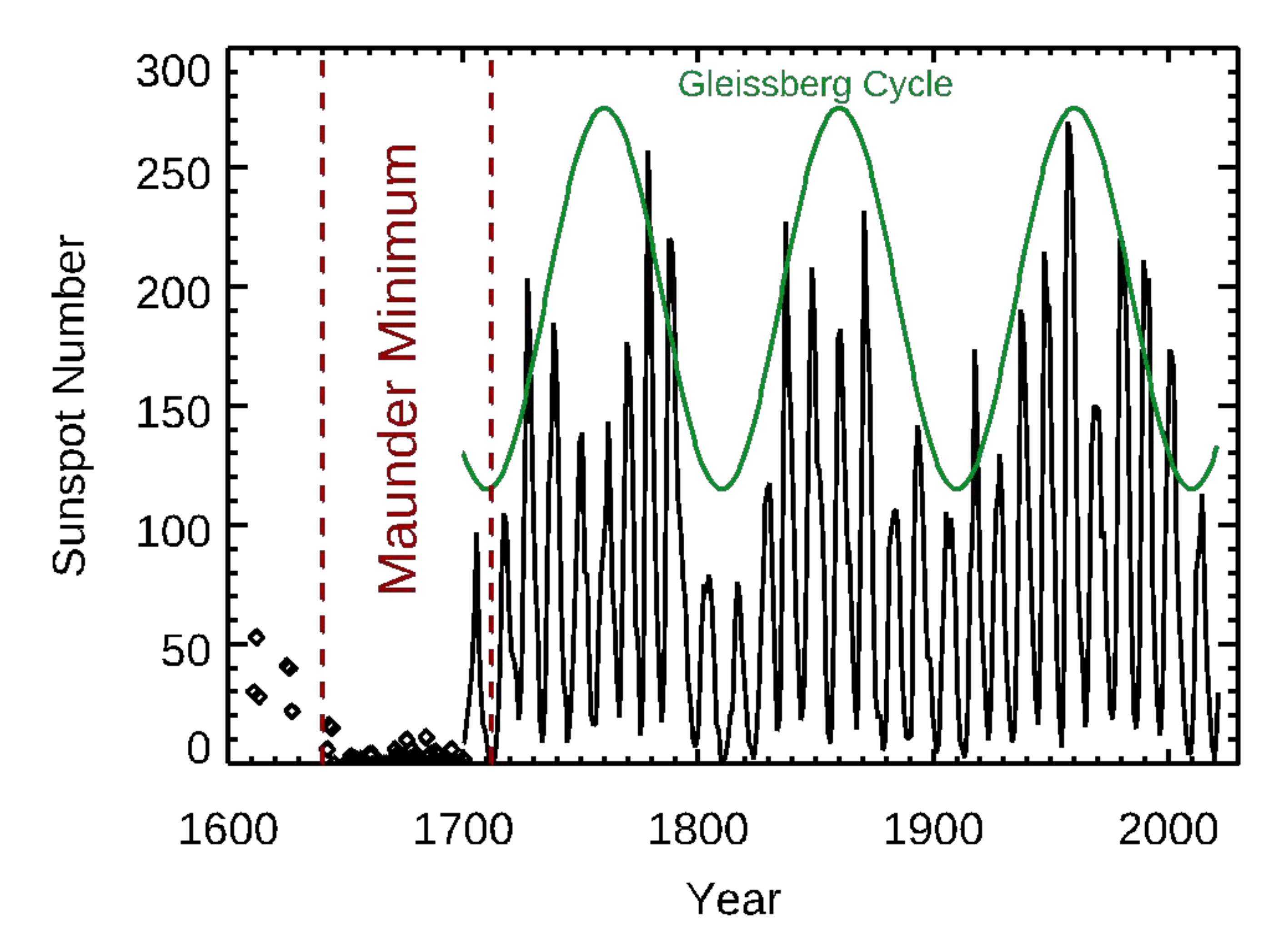
There is hint for 2019-2020 being lower than 2008-2009.
Figure 14 in Woods et al., *Solar Phys.*, 2022

Solar-proxy Record

Sunspot Number (SSN) is longest direct solar record. Maunder Minimum, ~100-year Gleissberg Cycle

The 4-century SSN record reveals the Gleissberg cycle and a period of low solar activity in the late 1600s called the Maunder Minimum.

Cooler temperatures in the 1600s on Earth are associated with the Maunder Minimum.



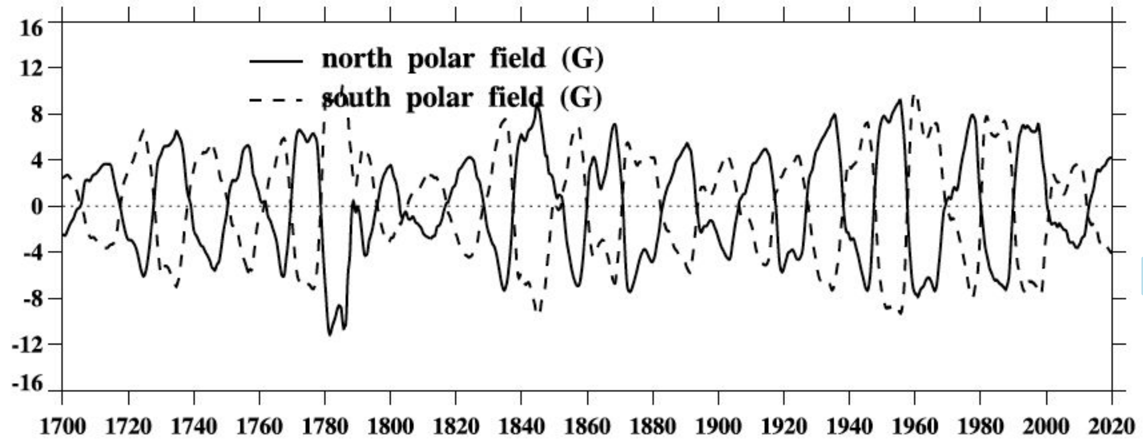
<u>Other 400+ Year Proxies</u>

Solar Magnetic Field: e.g. Wang & Lean, 2021

Geomagnetic Field: e.g. Svalgaard, 2016

Sunspot Number (SSN) for 1700-2022 is from WDC-SILSO. SSN before 1700 is estimate from Eddy (1976).

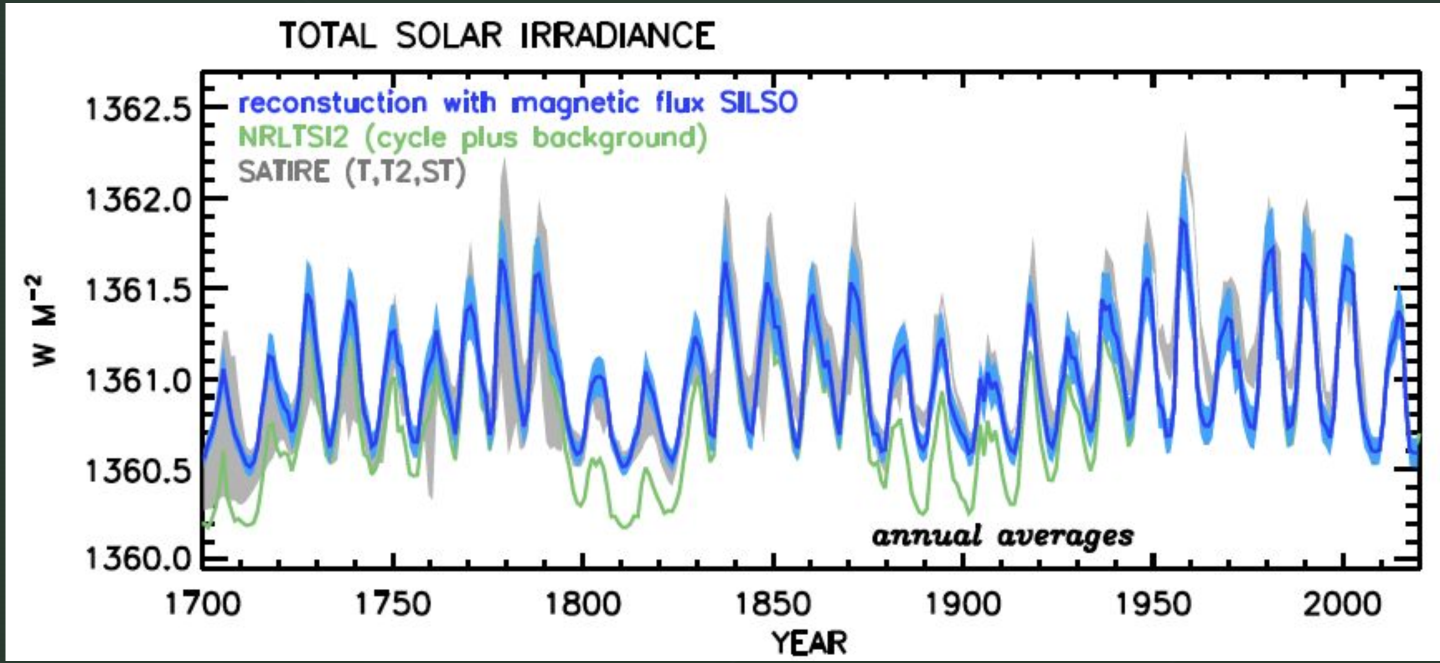
~100-year Gleissberg Cycle: Example by Estimating Solar Magnetic Fields with SSN



- Solar magnetic field estimates are made using SILSO SSN and varying the poleward flow velocity for the magnetic field.
- Solar polar field is good index for next cycle maximum.

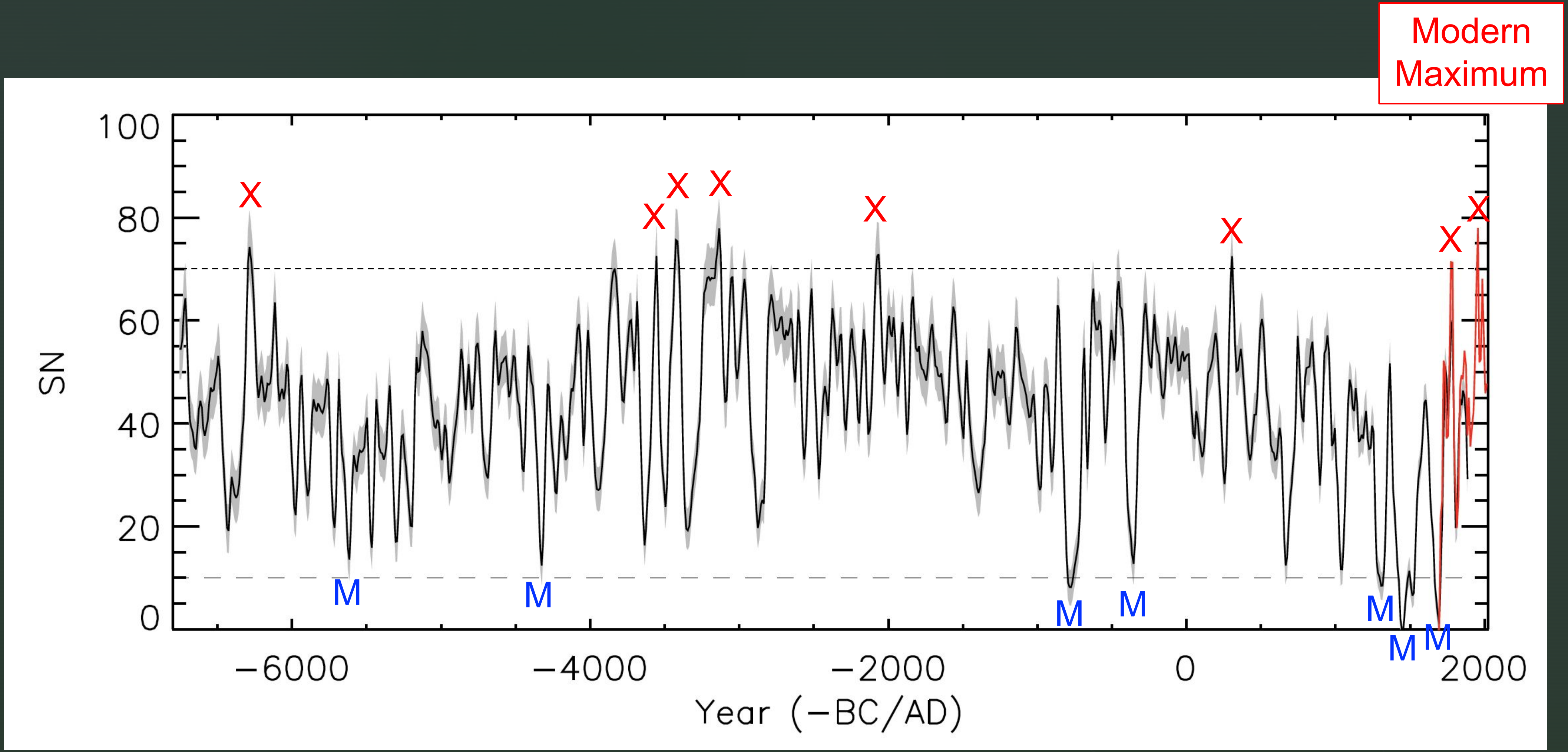
This reconstruction clearly shows Gleissberg minima.

1710: Maunder Minimum
1810: Dalton Minimum
1910: Gleissberg Minimum
2010: Modern Minimum



Maunder Minimum irradiance is similar to modern minima. Figures 3 amd 17 in Wang & Lean, *Astrophys. J.*, 2021.

Ice Cores provide proxy of solar activity for 9000 years Grand Minimum and Grand Maximum



^{10}Be and ^{14}C isotopes in ice cores are used to derive solar activity proxy

M = Grand Minima   X = Grand Maxima

This record also reveals ~2400-year Hallstatt Cycle.

Figure 14 in Chi Ju Wu et al., *Astron. Astrophys.*, 2018