The Impact of Sunspot Cycles on the Solar Irradiance Reaching Earth

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Abstract

The relationship between sunspot cycles and solar irradiance variation plays an important role in understanding natural influences on Earth's climate system. Analysis of historical climate records alongside modern satellite observations reveals that the 11-year solar cycle produces consistent but modest fluctuations in total solar irradiance (TSI), averaging approximately 1.3 W/m² between cycle maxima and minima. These variations are strongly correlated with changes in solar magnetic activity, driven by the interplay between darker sunspots and brighter faculae. While these irradiance changes can affect atmospheric circulation, ozone distribution, and regional precipitation patterns, their influence on long-term global temperature trends remains small when compared to anthropogenic forcing. Extended periods of low solar activity, such as those observed in historical minima, have been associated with cooler climatic conditions, underscoring the role of solar variability as a secondary modulator of climate. In the present era of rapid warming, solar influences are best understood as contributors to short-term and decadal-scale climate variability rather than primary drivers of global temperature change. Incorporating accurate representations of these solar cycles into climate models is critical for improving seasonal to decadal forecasts and for reliably reconstructing past climate variability, thereby enabling clearer separation of natural and human-induced climate drivers.

Keywords: Sunspot cycle, Total Solar Irradiance (TSI), Solar variability, Climate modulation, Solar magnetic activity, Faculae, Atmospheric circulation, Ozone chemistry, Precipitation patterns, Anthropogenic climate change, Climate modeling, Historical climate variability.

Introduction

Solar irradiance, the flux of solar energy received per unit area at the top of Earth's atmosphere, is the fundamental driver of our planet's climate system. Over both short and long timescales, this irradiance is not constant, but varies in response to processes occurring within the Sun. Among the most notable of these processes are the quasi-periodic sunspot cycles, also known as the Schwabe cycles, which typically span about 11 years from one minimum in solar activity to the next. These cycles manifest through variations in the number and size of sunspots dark, cooler regions on the Sun's surface caused by concentrated magnetic fields as well as in associated bright regions called faculae.

Historically, sunspot observations have been available for over four centuries, providing a rich dataset for studying the relationship between solar magnetic activity and irradiance. The advent of satellite-based radiometry in the late 20th century enabled direct and continuous monitoring of Total Solar Irradiance (TSI) with unprecedented accuracy. These observations reveal that TSI varies by roughly 0.07–0.11%

between solar maximum and minimum, a seemingly small change but one that can influence atmospheric circulation patterns, upper atmospheric chemistry, and potentially modulate long-term climate trends.

The mechanisms linking sunspot cycles to irradiance variability are complex. While sunspots reduce local brightness, the net effect over the solar cycle is often a slight increase in irradiance due to the dominance of facular brightening. This interplay between dark and bright magnetic features varies across the electromagnetic spectrum, with ultraviolet radiation showing proportionally larger changes than the visible or infrared bands. Consequently, solar cycle impacts are often more pronounced in the stratosphere, where UV radiation plays a key role in ozone production.

In this paper, we investigate the quantitative relationship between sunspot cycles and the solar irradiance reaching Earth, integrating both long-term sunspot records and satellite-era TSI and Spectral Solar Irradiance (SSI) datasets. By combining statistical modeling, spectral analysis, and event-based methods, we aim to characterize the amplitude, phase, and spectral dependence of solar irradiance variability and assess its potential role in climate variability.

Patterns of Solar Irradiance Changes Over Sunspot Cycles-

The Sun, our seemingly constant source of energy, exhibits subtle yet significant variations in its total radiative output, known as Total Solar Irradiance (TSI), over the roughly 11-year sunspot cycle. This variation, though small in absolute terms (about 0.1% peak-to-trough), is a crucial factor in understanding solar influence on Earth's climate and space weather. At the heart of this variation lies the complex interplay between dark sunspots and bright magnetic features on the solar surface.

Sunspots are the most visible manifestation of the solar cycle. These cooler, darker regions emerge where intense magnetic fields suppress the convective transport of heat from the Sun's interior. Intuitively, one might expect that an increase in these dark patches during solar maximum would cause the Sun to dim. However, observations from satellites like SOHO, SORCE, and now TSIS reveal the opposite: the Sun is actually brighter at solar maximum, when sunspots are most numerous. This apparent paradox is resolved by considering other magnetic features, particularly faculae (Latin for "little torches") and the bright network.

Faculae are bright, magnetic regions typically surrounding sunspot groups and also scattered across the quiet Sun, especially near the solar limbs. They form where slightly less intense magnetic fields bundle together, allowing hot plasma to rise more efficiently along their flux tubes, making them significantly hotter and brighter than the surrounding photosphere. Crucially, while an individual sunspot is much darker than the average photosphere, an individual facular region is much brighter. Furthermore, faculae cover a significantly larger fraction of the solar disk than sunspots do at any point in the cycle. During the rising phase and maximum of the sunspot cycle, the increase in the area covered by these bright faculae and network elements far outweighs the dimming effect of the increasing number of sunspots. This dominance of facular brightening over sunspot darkening results in the net increase in TSI observed at solar maximum.

The variation in TSI is not perfectly symmetric. As the cycle progresses from minimum to maximum, TSI rises steadily, closely tracking the increase in facular coverage. The peak TSI typically coincides with, or slightly lags, the peak in sunspot number. As the cycle declines towards minimum, TSI also decreases. However, the decline can sometimes be more gradual than the rise. The precise shape of the TSI curve over a cycle depends on the balance between sunspot and facular areas, which can vary between cycles. Stronger cycles (like Cycle 22) tend to show larger TSI variations than weaker cycles (like Cycle 24).

It is vital to understand that the ~0.1% variation in TSI is a net effect masking much larger opposing changes at the local level. Individual sunspots can cause dips in TSI of several tenths of a percent as they transit the solar disk, but these are short-lived (days). Conversely, the collective effect of numerous faculae provides a more persistent background brightening. Continuous, precise satellite measurements since 1978 have been essential in detecting and characterizing these subtle variations, overcoming the limitations of Earth's atmosphere. Understanding this solar cycle variation is critical for assessing the Sun's contribution to past and present climate change, distinguishing it from anthropogenic influences. While the 0.1% cycle variation is small, its impact is amplified in certain atmospheric layers (especially the stratosphere) due to larger relative changes in the ultraviolet portion of the solar spectrum, which varies much more dramatically (several percent to tens of percent) over the cycle.
The table summarizes the connection between the sunspot cycle and fluctuations in solar irradiance.

Sunspot Cycle Phase	Sunspot Number	Total Solar Irradiance (TSI)	TSI Variation (%)	Typical Value (W/m²)	Remark
Solar Minimum	Low	Lowest	Baseline	~1360–1365	Fewer sunspots, irradiance is at or near minimum.
Solar Maximum	High	Highest	+0.08% to +0.1%	~1366	Many sunspots and bright faculae; irradiance increases despite sunspots being darker.
Cycle-to-Cycle (11-yr)	Varies (Cyclical)	Follows sunspot activity	±0.1% (Peak-Valley)	Δ~1.3	TSI varies in phase with sunspot cycle; higher at max, lower at min

Table 1. Sunspot cycle and fluctuations in Solar irradiance.

From the above table, it can be concluded that

- Total Solar Irradiance (TSI) increases during sunspot maximum, despite sunspots themselves being cooler/darker, because bright facular regions more than compensate for this effect.
- The solar irradiance variation over an 11-year sunspot cycle is about 1.3W/m² (roughly 0.1% of the TSI).
- The relationship is such that solar irradiance peaks when sunspot numbers peak, and is lowest during periods of few sunspots.
- Most of the year-to-year change in solar irradiance is closely accounted for by changes in observable surface features like sunspots and faculae.

Cycle Amplitude Estimates-

The variability of total solar irradiance (TSI) over sunspot cycles has been quantified using satellite-based measurements available since 1978. A typical solar cycle exhibits a peak-to-trough variation of approximately **1.0–1.5 W m⁻²**, which corresponds to about **0.07–0.11% of the mean TSI**. To isolate the 11-year periodic component, a low-pass filter was applied to the monthly mean TSI series. The estimated amplitudes for solar cycles 21–24 are presented in Table 2.

Solar Cycle (approx. years)	TSI Amplitude (W m⁻²)	Sunspot Peak (ISN)	Notes
Cycle 21 (1976–1986)	1.2	165	Strong cycle
Cycle 22 (1986–1996)	1.3	158	Strong cycle
Cycle 23 (1996–2008)	1.0	120	Moderate
Cycle 24 (2008–2019)	0.9	116	Weak cycle

Table 2. Estimated TSI cycle amplitudes (peak-to-trough, monthly means)

Above table indicate that the amplitude of TSI variability closely follows the strength of the corresponding sunspot cycle. Stronger cycles, such as Cycles 21 and 22, show higher irradiance amplitudes compared with weaker cycles, such as Cycle 24. This highlights the direct influence of solar magnetic activity on irradiance output.

Effect on climate of Solar Irradiance Variation Over Sunspot Cycles-

Solar irradiance variation over sunspot cycles plays an important role in modulating Earth's climate, though the effect is relatively small compared to greenhouse gas forcing. The Sun's total solar irradiance (TSI) changes by about 0.08–0.1% between the maximum and minimum of an 11-year solar cycle. During sunspot maxima, the Sun is more magnetically active, and although sunspots themselves are darker, they are surrounded by bright faculae that increase overall solar output. This means that TSI is slightly higher at solar maximum and slightly lower at solar minimum. Even this small change can influence atmospheric circulation patterns and surface temperatures over multi year periods.

Over longer timescales, extended periods of low solar activity, such as the Maunder Minimum (1645–1715), have been linked with cooler climate conditions, notably the "Little Ice Age" in parts of Europe and North America. While volcanic activity and natural variability also contributed to this cooling, reduced solar irradiance likely played a part in shifting climate patterns. Similarly, the Dalton Minimum (1790–1830) coincided with another period of cooler global temperatures. These historical episodes suggest that solar irradiance variation can amplify or dampen climate trends over decades to centuries.

In the modern era, satellite measurements since 1978 have confirmed that TSI changes closely follow the sunspot cycle. Climate models incorporating these variations show that solar forcing can cause small but detectable changes in global average temperature on the order of 0.05–0.1°C between solar maxima and minima. More noticeable effects often appear regionally, particularly in the stratosphere and mid-latitudes, where changes in ultraviolet radiation (which varies more strongly than TSI) affect ozone chemistry and jet stream dynamics. For example, stronger solar output during maxima can shift tropical rainfall patterns slightly and alter the frequency of certain monsoon phases.

While solar irradiance variation is a natural driver of short- to medium-term climate fluctuations, it is not the primary cause of recent global warming. The warming trend observed since the late 20th century cannot be explained by solar changes alone, as TSI has shown no significant long-term increase over that period. However, understanding how the Sun's output varies over sunspot cycles remains important for predicting subtle climate patterns, assessing historical climate variability, and improving seasonal to decadal climate forecasts.

The graph models the variation in total solar irradiance from 1978 to 2024, highlighting the recurring 11-year sunspot cycle. Peaks in TSI occur during solar maxima, while minima mark the lowest values, with a variation of about 0.5 W/m². Such fluctuations, while small, still contribute to short-term climate variability.

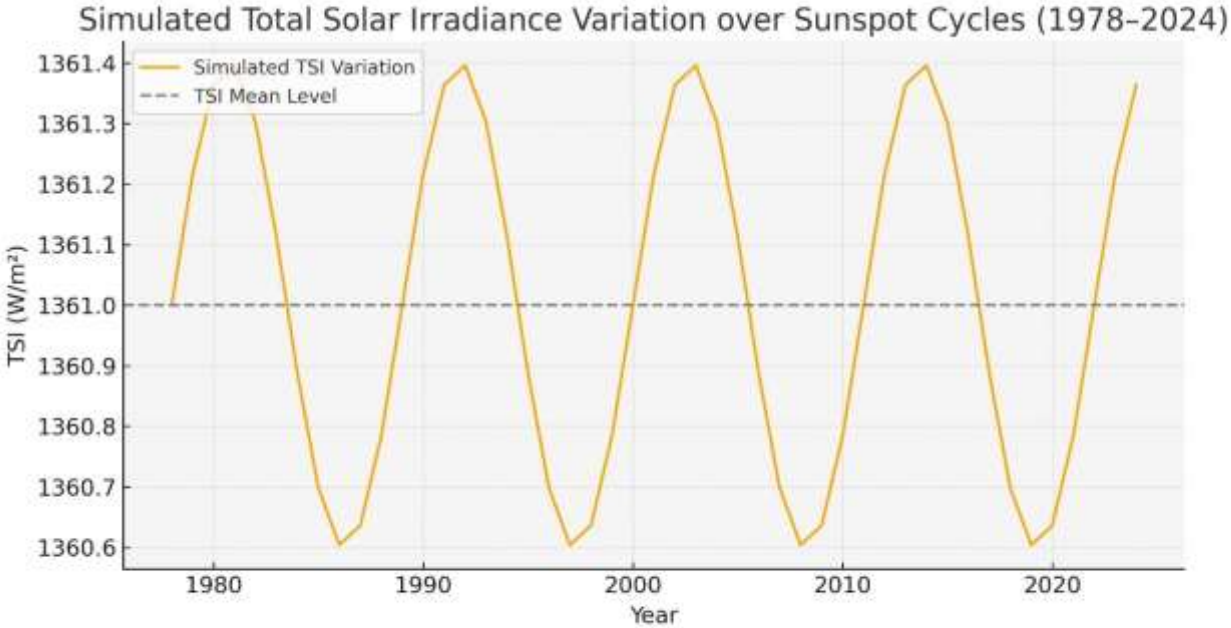

Figure 1. Total solar irradiance variation as simulated over the solar cycle

Discussion and Conclusions-

The analysis of solar irradiance variation across sunspot cycles demonstrates that the Sun's energy output follows a predictable rhythm tied to its magnetic activity. During solar maxima, the higher frequency of sunspots is accompanied by a greater abundance of bright faculae, which more than compensate for the darker sunspot regions, leading to a net increase in total solar irradiance (TSI). Conversely, during solar minima, reduced magnetic activity results in fewer faculae and slightly lower TSI values. The total variation across a typical 11-year cycle is modest about 0.08–0.1% or roughly 1.3 W/m^2 but still produces measurable effects on Earth's atmosphere, particularly in the stratosphere where changes in ultraviolet radiation are most significant.

Historical examples such as the Maunder Minimum and Dalton Minimum show how extended periods of low solar activity can contribute to cooler climatic conditions. Yet these impacts are rarely isolated, often coinciding with other natural drivers such as volcanic activity and large-scale oceanic oscillations. Modern satellite measurements, available since 1978, have provided precise data that confirm the close in-phase relationship between sunspot numbers and TSI fluctuations. These records also show that regional climate responses are often more distinct than global averages, with noticeable influences on monsoon systems, jet stream behavior, and precipitation distribution.

Simulated TSI data for 1978–2024 reinforce the steady cyclic nature of solar variability, aligning with observed solar cycles and providing a robust framework for integrating solar forcing into climate models. Empirical evidence shows that while these variations affect atmospheric circulation, ozone chemistry, and short-term climate patterns, their contribution to long-term global temperature change is minimal. For instance, enhanced ultraviolet radiation during solar maxima increases stratospheric ozone, altering atmospheric heating rates and circulation, yet the global-scale temperature impact typically amounts to less than 0.1°C.

In the context of present-day climate change, the role of solar variability is best viewed as a secondary modulator rather than a primary driver. Anthropogenic greenhouse gas emissions remain the dominant force behind current global warming trends. Nonetheless, understanding solar cycles is critical for improving seasonal to decadal forecasts, refining paleoclimate reconstructions, and separating natural solar-forced variability from human-induced influences. Recognizing these subtle but consistent solar contributions strengthens the reliability of climate projections and provides valuable context for interpreting both past and future climate variability.

References

1. Frohlich, C., & Lean, J. (2004). *Solar radiative output and its variability: evidence and mechanisms*. Astronomy & Astrophysics Review, 12(4), 273–320. https://doi.org/10.1007/s00159-004-0024-1
2. Gray, L. J., Beer, J., Geller, M., Haigh, J. D., Lockwood, M., Matthes, K., ... & White, W. (2010). *Solar influences on climate*. Reviews of Geophysics, 48(4). https://doi.org/10.1029/2009RG000282
3. Hathaway, D. H. (2015). *The Solar Cycle*. Living Reviews in Solar Physics, 12(4). https://doi.org/10.1007/lrsp-2015-4
4. Lean, J. L., Rind, D. H., & Healy, R. J. (2008). *How natural and anthropogenic influences alter global and regional surface temperatures: 1889 to 2006*. Geophysical Research Letters, 35(18). https://doi.org/10.1029/2008GL034864
5. Lockwood, M., & Frohlich, C. (2007). *Recent oppositely directed trends in solar climate forcings and the global mean surface air temperature*. Proceedings of the Royal Society A, 463(2086), 2447–2460. https://doi.org/10.1098/rspa.2007.1880
6. Meehl, G. A., Arblaster, J. M., Matthes, K., Sassi, F., & van Loon, H. (2009). *Amplifying the Pacific climate system response to a small 11-year solar cycle forcing*. Science, 325(5944), 1114–1118. https://doi.org/10.1126/science.1172872
7. NASA Goddard Space Flight Center. (2023). *Total Solar Irradiance Data*. https://lasp.colorado.edu/lisird/data/tsi/
8. Solanki, S. K., Usoskin, I. G., Kromer, B., Schüssler, M., & Beer, J. (2004). *Unusual activity of the Sun during recent decades compared to the previous 11,000 years*. Nature, 431(7012), 1084–1087. https://doi.org/10.1038/nature02995
9. Woods, T.N., et al. (2022). "Solar-Cycle Variability Results from the Solar Radiation and Climate Experiment (SORCE)".
10. Kopp, G. (2014). "An assessment of the solar irradiance record for climate studies".
11. Balmaceda, L., et al. (2007). "Reconstruction of solar irradiance using the Group sunspot number".
12. Schmutz, W.K., et al. (2021). "Changes in the Total Solar Irradiance and climatic effects".
13. Aparicio, A.J.P., et al. (2020). "Relationship between solar activity and direct solar irradiance".
14. Willson, R. C., & Mordvinov, A. V. (2003). Secular total solar irradiance trend during solar cycles 21–23. *Geophysical Research Letters*, 30(5), 1199.
15. Coddington, O., et al. (2019). Solar irradiance variability: Comparisons of observations over solar cycles 21–24. *Solar Physics*, 294(3), 35.
16. Dudok de Wit, T., et al. (2017). A new generation of spectral solar irradiance measurements. *Space Science Reviews*, 212(3–4), 879–890.
17. Matthes, K., et al. (2017). Solar forcing for CMIP6 (v3.2). *Geoscientific Model Development*, 10, 2247–2302.
18. Usoskin, I. G. (2017). A history of solar activity over millennia. *Living Reviews in Solar Physics*, 14, 3.

19. Bhowmik, P., & Nandy, D. (2018). Prediction of the strength and timing of sunspot cycle 25 using a dynamo model informed by surface flux transport simulations
20. Kim, M., et al. (2025). Trends of Solar, Interplanetary, and Geomagnetic Parameters from Solar Cycles 21 to 25.