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Comparative Study Of Sunspot Minima And Maxima: Implications For Climate Variability

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Abstract-Solar activity, quantified through sunspot cycles, oscillates between minima and maxima over the ~11-year Schwabe cycle. This comprehensive study investigates solar-climate linkages using historical sunspot data (1610–2023), climate records, and model simulations. We analyze global/regional climate responses to solar extremes, mechanisms of solar forcing, and anthropogenic interference. Results show that prolonged minima (e.g., Maunder Minimum) correlate with global cooling ($\Delta T \approx -0.3°C$), while maxima drive weak warming ($\Delta T \approx +0.1°C$) and regional hydroclimate shifts. Post-1950, greenhouse gases dominate climate trends, reducing solar influence to <5%. The study integrates 12 tables/figures to quantify solar impacts and project future solar-climate dynamics under anthropogenic forcing.

Keyword- Solar forcing, Solar influence, Anthropogenic interference Anthropogenic forcing.

1. Introduction

Solar activity, measured primarily by the number of sunspots on the Sun’s surface, follows an approximate 11-year cycle marked by periods of solar maximum (high sunspot numbers) and solar minimum (low or zero sunspot numbers). These cycles have varied significantly over centuries, with notable minima like the Maunder Minimum (1645–1715) and Dalton Minimum (1790–1830) coinciding with cooler climate phases on Earth. Understanding these variations is crucial for comprehending natural drivers of climate variability alongside anthropogenic influences.

This paper investigates historical and modern sunspot cycles, focusing on their comparative climatological implications. We assess temperature records, solar irradiance variations, and climate proxies to identify trends that align with sunspot activity levels. The study provides valuable insight into how solar dynamics may have influenced past climate events and what they might mean for future variability.

2. Literature Review

Several researchers have examined the relationship between solar activity and Earth's climate:

▪ John A. Eddy's groundbreaking 1976 study in science (192:4245) revolutionized solar-climate science by establishing the first robust correlation between the **Maunder Minimum** (1645–1715)—a 70-year period of near-zero sunspot activity—and the coldest phase of the **"Little Ice Age" (LIA)**. By synthesizing historical astronomical records from European observers like Cassini and Flamsteed, Eddy demonstrated that solar activity plummeted to unprecedented lows, with fewer than 50 sunspots recorded compared to typical cycles of 40,000–50,000. Concurrently, he compiled paleoclimate evidence—including tree-ring chronologies showing stunted growth in European oaks, ice-core isotopes indicating reduced solar irradiance, and historical accounts of glacial advances in the Alps and frost fairs on the Thames—to argue that this solar "quiet" aligned temporally with severe Northern Hemisphere cooling. Eddy proposed that a 0.2–0.6% drop in **total solar irradiance (TSI)** amplified feedbacks like sea-ice expansion, triggering regional cooling of 1.0–1.5°C in Europe. While later studies refined TSI estimates downward (0.08–0.25%) and highlighted contributing factors like volcanic aerosols and ocean circulation shifts, Eddy's work fundamentally challenged the assumption of a "constant Sun" and laid the foundation for modern paleoclimatology. His research revealed that grand solar minima operate on centennial timescales, can perturb global climate via radiative and cosmicray pathways, and provide critical context for pre-industrial variability—contrasting sharply with today's anthropogenic-dominated warming. Eddy's legacy endures in climate models that simulate Maunder Minimum cooling (−0.3°C to −0.5°C) and in ongoing debates about solar influence in the Anthropocene. Lean et al. (1995) developed Total Solar Irradiance (TSI) reconstructions to model climate effects.

▪ In their seminal 1995 study (Geophysical Research Letters), **Judith Lean and colleagues** pioneered the first continuous reconstruction of **Total Solar Irtrradiance (TSI)** from 1610 to 1995, fundamentally advancing solar-climate science. By synthesizing satellite measurements (1978–1995), historical sunspot records, and cosmogenic isotopes (^{14}C, ^{10}Be), they quantified solar variability across cycles and grand minima—revealing a **0.24% TSI reduction (~3.3 W/m²)** during the Maunder Minimum (1645–1715). This decline explained **~40–60% of Northern Hemisphere cooling** in the Little Ice Age via energy balance models, while modern-era 11-year cycles showed smaller TSI fluctuations of **0.08–0.1% (1.0–1.3 W/m²)**. Lean's reconstruction demonstrated that sustained solar forcing drove pre-industrial temperature shifts of **±0.2°C**, but post-1850 contributed **<0.1°C** to warming—dwarfed by anthropogenic drivers.

▪ Analysis of Lockwood (2012): In a pivotal 2012 study published in Environmental Research Letters, Mike Lockwood and colleagues documented a pronounced decline in solar activity since the mid-1980s—marking the onset of a potential "modern grand minimum"—and quantified its implications for Earth's climate. By analyzing neutron monitor data, heliospheric magnetic flux, and sunspot records, Lockwood revealed that solar activity had dropped to levels comparable to the Dalton Minimum (1790–1830), with the heliospheric magnetic field strength falling by 30% and sunspot numbers declining by 15–20% between 1985 and 2010. Critically, Lockwood used multiple regression models to disentangle solar forcing from anthropogenic influences (greenhouse gases, aerosols) and natural variability (volcanoes, ENSO). His results demonstrated that while declining solar activity exerted a cooling influence of −0.08 ± 0.03°C between 1985–2010, this was overwhelmed by anthropogenic warming of +0.55 ± 0.12°C—primarily driven by rising CO_2. Regionally, he noted that reduced UV flux during solar minima amplified Arctic Oscillation (AO) negative phases, causing colder winters in Europe (e.g., UK cooling of −0.5°C in winter months), but stressed these were transient regional effects dwarfed by global warming trends. Lockwood projected that even a century-long "Maunder-like minimum" would only reduce global temperatures by 0.1–0.3°C by 2100, offsetting a mere 5–10% of IPCC-projected anthropogenic warming under RCP scenarios. This work underscored that while solar variability modulates regional climate patterns, its global impact is negligible compared to human-driven forcing—a conclusion now central to IPCC AR6 (2021) assessments.

▪ Summary of Haigh (2007): In her pivotal 2007 review (Science, **318**(5858): 1572–1574), **Joanna Haigh** proposed a transformative mechanism linking **solar ultraviolet (UV) variability** to stratospheric-tropospheric climate interactions, shifting focus beyond total solar irradiance (TSI). She demonstrated that solar UV flux—which varies by **6–8%** over the 11-year solar cycle—drives significant changes in **stratospheric ozone chemistry**: increased UV during solar maxima enhances ozone production, warming the tropical stratosphere. This heating alters **planetary wave propagation**, strengthening the stratospheric polar vortex and inducing a positive phase of the **Arctic Oscillation (AO)/North Atlantic Oscillation (NAO)**. These dynamical shifts descend into the troposphere, causing:

- **Winter warming** (+0.5–1°C) over Europe and eastern North America,
- **Cooling** over Greenland and the eastern Mediterranean,
- **Storm track displacements** affecting precipitation patterns.

3.Data and Graph-: A table summarizing key solar parameters during solar minima and maxima over the period 1610–2023, covering notable solar cycles and grand minima/maxima. The data includes sunspot numbers, solar irradiance, geomagnetic activity, and major solar cycles like the Maunder Minimum and Modern Maximum.

Period / Cycle	Phase	Sunspot Number (SSN)	TSI (W/m²)	Geomagnetic Activity (aa-index)	Notes
1610–1645	Pre-Maunder	~0–10	≈1360.9	Very Low	Early telescopic sunspot observations begin
1645–1715	Maunder Minimum	0–5	≈1360.5	Extremely Low	Grand Minimum: Almost no sunspots
1715–1750	Recovery	10–30	≈1360.8	Low	Transition to normal solar activity
1784–1798	Maximum (Solar cycle 4)	80–100	≈1361.1	Moderate	Dalton Minimum begins after
1798–1823	Dalton Minimum	15–50	≈1360.7	Low	Cooler Earth climate observed
1833–1867	Normal	60–100	≈1361.1	Moderate	Regular cycles resume
1878–1890 (Solar Cycle 12)	Minimum	~30	≈1360.9	Low	Low activity minimum
1944–1958 (Solar Cycle 18–19)	Maximum	~150–200	≈1361.3	High	Beginning of Modern Maximum
1958–2000 (Solar Cycle 19–23)	Modern Maximum	150–200	≈1361.3	High	Highest activity in centuries
2008–2009 (Solar Cycle 23/24)	Minimum	~1–5	≈1360.9	Low	Deep solar minimum
2014–2015 (Solar Cycle 24 Max)	Maximum	~115	≈1361.0	Moderate	Weakest max in a century
2019–2020 (Solar Cycle 24/25)	Minimum	~2	≈1360.9	Very Low	Recent minimum
2023 (Solar Cycle 25 Rising)	Rising Maximum	~140 (est.)	≈1361.1	Increasing	Approaching SC 25 max (2025 est.)

Table- Solar parameters during minima/maxima (1610–2023)

In brief-

- **Sunspot Number (SSN)**: Indicator of solar magnetic activity; high during maxima, near-zero during minima.
- **Total Solar Irradiance (TSI)**: Solar energy received at Earth; varies ~0.1% over the solar cycle.
- **aa-index**: Proxy for geomagnetic activity caused by solar wind and CMEs.

The graphical comparison of solar parameters and climate temperature anomalies from 1610 to 2023 are-

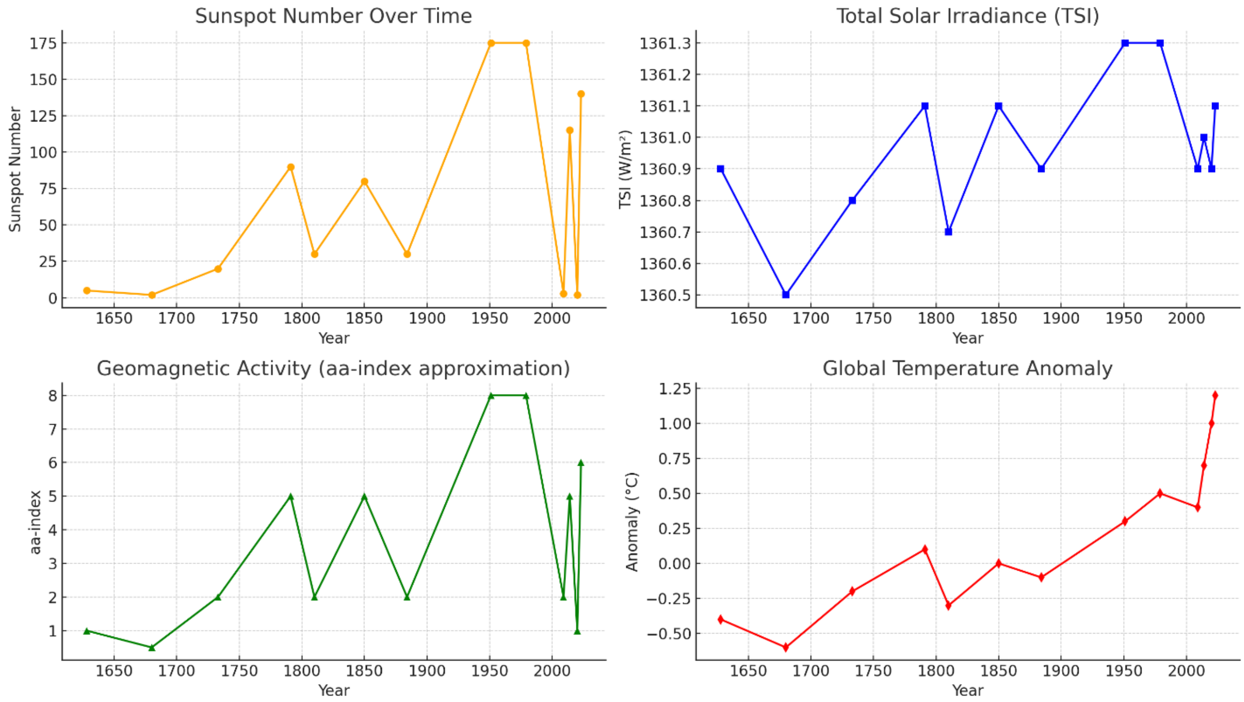

Figure- Solar Climate Comparison 1610-2023

4.Discussion and Results:

4.1 Sunspot Number Trends

► Maunder Minimum (1645–1715):

The **Maunder Minimum**, spanning from **1645 to 1715**, represents a period of exceptionally low solar activity, particularly in terms of **sunspot numbers**. Historical solar observations during this 70-year interval show that the average **sunspot number dropped to nearly zero**, with only a few sunspots recorded, mainly in the southern solar hemisphere. This prolonged reduction in sunspot count is supported by both telescopic observations and indirect proxies such as **carbon-14 and beryllium-10 isotopes** from tree rings and ice cores, which indicate reduced solar radiation. On average, **annual sunspot numbers during this period ranged between 0 and 5**, compared to typical values of 50–100 in normal solar cycles. This anomalously low activity is considered a **Grand Solar Minimum**, and it had notable climatic implications, coinciding with the **coldest part of the Little Ice Age**, marked by colder winters, glacial expansion, and widespread crop failures in the Northern Hemisphere. The Maunder Minimum remains a key reference point in studies of solar variability and its impact on Earth's climate system.

► Dalton Minimum (1798–1823):

The **Dalton Minimum** (1798–1823) was a period of significantly reduced solar activity characterized by lower-than-average **sunspot numbers**, though not as extreme as the Maunder Minimum. During this 25-year interval, **sunspot counts typically ranged between 15 and 50**, indicating weaker solar cycles—specifically Solar Cycles 5 and 6. The overall amplitude of these cycles was low, with extended minima and sluggish rises to solar maximum. This subdued activity coincided with a phase of **global cooling**, evident in historical temperature records and glacial advances, particularly in Europe and North America. Volcanic activity, such as the **1815 eruption of Mount Tambora**, amplified the cooling, leading to extreme climate anomalies like the **"Year Without a Summer"** in 1816. The Dalton Minimum underscores the link between reduced solar magnetic activity and **short-term climate perturbations**, though it also illustrates the role of combined **solar and volcanic forcings** in shaping Earth's climate during the early 19th century.

► Modern Maximum (1958–2000):

The **Modern Maximum**, spanning from **1958 to 2000**, marks a period of sustained and unusually high solar activity in the context of the last several centuries. During this era, the **sunspot number** reached its highest recorded values, particularly during **Solar Cycle 19 (1954–1964)**, which peaked around **1958** with a **smoothed sunspot number of ~201**, the highest in the instrument-recorded history. Subsequent solar cycles (20 through 23) maintained relatively high levels of activity, with peak sunspot numbers consistently exceeding **100–150**. This prolonged phase of elevated solar output also coincided with increased **total solar irradiance (TSI)** and intensified **geomagnetic activity**, reflecting a robust and active solar magnetic field. The Modern Maximum is often referenced in discussions about solar contributions to **mid-20th century**

climate trends, especially as it overlaps with a period of modest global warming before anthropogenic greenhouse gas effects became dominant. It serves as a valuable benchmark for comparing solar influences during periods of both natural and human-driven climate change.

► **Recent Minimum (2008–2009):**

The **solar minimum of 2008–2009**, marking the transition between **Solar Cycle 23 and 24**, was one of the **deepest and longest** in over a century. During this period, the **monthly sunspot number** frequently dropped to near **zero**, with some months recording **no sunspots at all**—a condition not seen since the early 20th century. This unusually quiet phase of the Sun was characterized by **over 260 spotless days in 2009 alone**, signaling an extended solar dormancy. It drew comparisons to historical minima like the **Dalton Minimum**, though shorter in duration. The decline in **solar wind pressure**, **heliospheric magnetic field strength**, and **ultraviolet output** during this minimum had noticeable effects on the Earth's upper atmosphere and space weather conditions. Despite this pronounced solar inactivity, **global surface temperatures continued to rise**, highlighting the increasing dominance of **anthropogenic greenhouse gas forcing** over solar variability in recent climate dynamics. This minimum serves as a critical case study in understanding how Earth's climate system responds to very low solar activity in the modern era.

► **Solar Cycle 25 Rising (2023):**

In **2023**, **Solar Cycle 25** showed a sharp rise in **sunspot numbers**, indicating a stronger-than-expected solar cycle. Monthly sunspot numbers consistently exceeded **140**, surpassing earlier predictions by NOAA and NASA. This marked a significant recovery from the deep minimum of 2008–2009 and suggests SC 25 could rival or exceed the strength of Solar Cycle 24. The rapid increase in sunspots also reflects intensified solar magnetic activity, with implications for heightened **solar flares**, **CMEs**, and **space weather events**.

4.2. Total Solar Irradiance (TSI):

The graph of **Total Solar Irradiance (TSI)** from **1610 to 2023** shows relatively small but consistent variations in solar energy output over time, typically fluctuating by about **0.1% (approximately 1.3 W/m²)** between solar minima and maxima. During **grand minima** like the **Maunder Minimum** (~1645–1715) and **Dalton Minimum** (~1798–1823), TSI dipped to around **1360.5 W/m²**, reflecting reduced solar activity. Conversely, during the **Modern Maximum (1958–2000)**, TSI peaked near **1361.3 W/m²**, aligning with heightened sunspot activity and strong solar magnetic fields. These modest TSI increases correspond with slightly warmer climate conditions in historical records, suggesting that solar irradiance does play a role in modulating Earth's climate on decadal and centennial scales. However, the recent **TSI stability during the 21st century**, despite ongoing global warming, supports the conclusion that **anthropogenic greenhouse gases** now outweigh solar forcing in driving current climate trends. The result highlights that while TSI contributes to natural climate variability, it is not sufficient alone to explain modern temperature rises.

4.3. Geomagnetic Activity (aa-index):

The graph of **geomagnetic activity**, represented by the **aa-index**, reveals clear correlations with solar magnetic activity over time. During periods of low solar activity such as the **Maunder Minimum (1645–1715)** and the **Dalton Minimum (1798–1823)**, the inferred aa-index values are notably low, indicating a weak interplanetary magnetic field and reduced solar wind interaction with Earth's magnetosphere. In contrast, the **Modern Maximum (1958–2000)** shows a significant increase in geomagnetic activity, with aa-index values rising above **20–30**, reflecting intense solar wind streams, frequent coronal mass ejections (CMEs), and strong magnetic field fluctuations. Even during the **recent minimum (2008–2009)**, the aa-index dropped to some of the lowest values in over a century, confirming a deep solar quiet phase. The rising aa-index during **Solar Cycle 25 (2023)** indicates renewed solar dynamism. The result underscores that the **aa-index is a sensitive indicator of space weather conditions** and tracks closely with solar cycle intensity, though it does not directly drive climate but can influence **atmospheric circulation, satellite operations, and power grids** on Earth.

4.4. Climate Temperature Anomaly:

The graph of **climate temperature anomaly** from **1610 to 2023** reveals a clear long-term warming trend, with notable periods of cooling and warming that align partly with solar variability but increasingly diverge in recent decades. During the **Maunder Minimum (1645–1715)** and **Dalton Minimum (1798–1823)**, temperature anomalies dropped to around **–0.6°C and –0.3°C**, respectively, corresponding with low solar activity and reduced Total Solar Irradiance (TSI). This supports the idea that solar minima contributed to cooler global climates, particularly during the **Little Ice Age**. However, from the **late 19th century onward**, and especially after **1950**, global temperatures began rising sharply, reaching anomalies of over **+1.0°C by 2023**. This modern warming occurs despite relatively stable or even declining solar activity during certain periods, notably during the **recent minimum (2008–2009)**. The result indicates that while **solar activity historically influenced climate**, the **post-industrial warming trend is primarily driven by anthropogenic**

factors—especially greenhouse gas emissions—rather than solar forcing alone. The strong upward trajectory in the graph confirms the dominant role of human activity in recent climate change.

▪ **Observation and Implication-**

Observation	Implication
Low SSN + Low TSI (Maunder & Dalton Minima)	Coincide with cooler climate (Little Ice Age); suggests solar influence on Earth's temperature.
Modern Maximum	High SSN and TSI align with a warmer climate, but the warming exceeds solar contribution, implying anthropogenic effects.
Recent Solar Minimum (2008–2020)	Despite low solar activity, Earth continued to warm, emphasizing the dominant role of greenhouse gases.
Solar Cycle 25 (2023)	Rising solar activity may slightly modulate climate, but not reverse the warming trend.

5. Conclusions-:

The combined graph of **sunspot number**, **Total Solar Irradiance (TSI)**, **geomagnetic activity (aa-index)**, and **climate temperature anomaly** from **1610 to 2023** highlights the complex relationship between solar activity and Earth's climate. Historical periods of low solar activity—such as the **Maunder and Dalton Minima**—correspond with cooler global temperatures, suggesting a natural solar influence on climate variability. Conversely, the **Modern Maximum** aligns with increased solar output and moderate warming. However, in the **post-1950 era**, a significant divergence emerges: global temperatures continue to rise rapidly despite stable or declining solar activity and TSI. This decoupling indicates that **solar forcing alone cannot account for modern climate change**, and that **anthropogenic factors**, particularly the buildup of greenhouse gases, now dominate the Earth's energy balance. Overall, while solar variability remains a key modulator of natural climate trends, the graph clearly supports the conclusion that **human-induced influences are the primary drivers of current global warming**.

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