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An Analysis of Solar Modulation of Cosmic Rays and Their Significance on Earth's Climate

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Abstract

Earth receives markedly higher solar irradiance during periods of high solar activity than during quiet conditions, and this variation has been considered here to study its bearing on galactic cosmic rays (GCRs) and, in turn, on climate. GCRs, being high-energy charged particles, get modulated by the heliospheric magnetic field carried outward by the solar wind, giving rise to the well-known anti-correlation, seen in neutron monitor data, between cosmic ray intensity and solar activity indices such as sunspot number, following an approximately 11-year cycle corresponding to half of the solar magnetic cycle. Modulation processes differ for positively and negatively charged particles and also vary with solar magnetic polarity. Here, the effects of outward and inward heliospheric field configurations, and of both solar magnetic polarities, on cosmic ray modulation have been examined, drawing on a literature-based synthesis of publicly archived solar, cosmic ray, and climate datasets, viz. WDC-SILSO, NMDB, and standard instrumental temperature compilations. Modulation of the terrestrial cosmic ray flux is considered as a possible solar influence on climate, acting through atmospheric ion production and electrical conductivity. Cloud nucleation associated with cosmic ray flux is also discussed, along with the balancing evidence from CERN's CLOUD experiment, which indicates that the amplification mechanism linking microphysical effects to macroscopic climate response is, at best, only partly quantified. Daily and monthly sunspot numbers over approximately two centuries are analysed, together with the open solar magnetic flux and the 6–12-month lag observed between solar and cosmic ray variability. The correlation between sunspot number and global surface temperature (GST) is found to lie in the range $r \approx 0.5$-0.7 for the pre-1980 record, weakening markedly thereafter, consistent with a growing dominance of greenhouse-gas forcing. The results, taken together, contribute to a more balanced understanding of the possible role of solar-modulated cosmic rays in climate variability.

Keywords

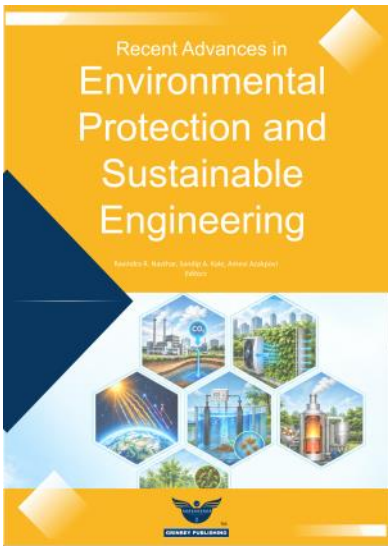
Solar Modulation; GCR; Heliospheric Magnetic Field; Sunspot Number; Climate Variability

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1. Introduction

The Sun is the main driver of all energy on Earth. The atmosphere surrounding Earth becomes turbulent because of the Sun's heat. The energy fluctuates over an 11-year cycle [1-4]. The total energy that reaches Earth during this cycle shifts by about 0.1%. During solar cycles, the Sun's energy gradually shifts. There are times when the Sun is more active. The lower atmosphere is warmed by ozone reactions. These reactions are brought on by intense UV radiation. The air at the North and South Poles is heated by geomagnetic activity. More sunlight can reach the ground when there are fewer clouds. This decrease in clouds is caused by fewer cosmic rays. The Earth heats up significantly in these minor alterations. Both short- and long-term climate conditions can be influenced by the Sun. On time scales ranging from 28 days to 12, 23, 81, 181 years, and beyond, the Sun's activity varies. Because it dominates the cooler sunspots, an active Sun is brighter. During solar maxima, our planet receives more radiation from the Sun than it does during solar minima. Earth's climate change is largely caused by a variety of indirect factors, including these radiative effects of solar variation. Monitoring eruptional activity over a specific time period has been shown to be essential for measuring solar irradiance.

2. Data sources and analytical approach

This study is based on a comparative, literature-informed analysis of publicly archived solar-terrestrial datasets rather than newly acquired observations. Daily and monthly sunspot numbers spanning approximately two centuries (1818-2020) were drawn from the World Data Center for the Sunspot Index and Long-term Solar Observations (WDC-SILSO), Royal Observatory of Belgium [5]. Cosmic ray intensity records were obtained from ground-based neutron monitor stations archived in the Neutron Monitor Database (NMDB) [6], and open solar magnetic flux estimates followed the reconstruction methodology of Lockwood et al. [2]. Global surface temperature (GST) anomalies, likewise, have been taken from standard instrumental compilations, viz. the Berkeley Earth record and the IPCC Sixth Assessment Report [7, 8]. The analysis, in essence, is a qualitative and semi-quantitative comparison of the temporal profiles of these several series - sunspot number, neutron monitor count rate, open solar flux and GST - over common time windows, and it is supplemented by correlation and lag estimates already reported in the cited literature rather than by any fresh statistical re-analysis of the raw series. Since the study synthesizes and cross-compares existing published records instead of presenting new experimental measurements, its principal contribution lies in bringing together, within a single framework, the observational evidence for solar-cosmic ray-climate coupling, and in pointing out the quantitative gaps - such as the lag between solar and cosmic ray variability and the strength of the sunspot-GST correlation - that are taken up numerically in Sections 6 and 7.

3. Heliospheric Propagation and Modulation of GCR

High-energy charged cosmic ray nuclei, present throughout interstellar space, are continually approaching the inner Solar System. The Sun, however, provides a natural defence against them: it continuously throws out a stream of ionized plasma, viz. the solar wind, and this forms a protective magnetic barrier around the heliosphere. This wind carries its own magnetic field; it creates a turbulent barrier that cosmic rays must fight to cross. Only the most energetic particles can successfully navigate this magnetic obstacle to enter the inner Solar System. As the ionized material expands away from the Sun, this intricate magnetic field structure stays "frozen" within it [9, 10]. According to research, solar wind particles near Earth have a mean kinetic energy of 600 MeV and range in velocity from 260 to 650 km/s. The mean interplanetary magnetic field strength near Earth is separately estimated at approximately 3-5 nT (~3×10^{-5}-5×10^{-5} G) [11]; being a distinct physical quantity governed by different physics, it is not directly comparable in magnitude to the particles' kinetic energy. Neutron monitor data and the Sun's sunspot numbers show an anti-correlation when

the solar system modulates galactic cosmic ray particles [12, 13]. Following an 11-year solar period - exactly 50% of the Sun's complete magnetic cycle - the sunspot number designates the solar active regions. Changes in the sunspot number are observed to occur one to two years later. Areas of outward and inward magnetic polarity are divided by the current sheet. This sheet is produced by a combination of the solar wind's radial flow and solar rotation. These inward (b) and outward (a) magnetic fields are shown in Figure 1.

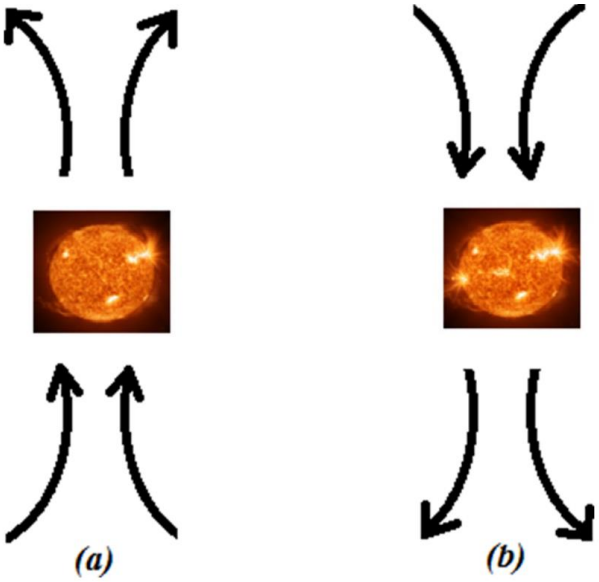


Fig.1. Magnetic field directed away (+ve polarity), (b) Magnetic field directed in (-ve polarity)

There is evidence that, depending on solar polarity, both positively and negatively charged particles modulate through different mechanisms. One important finding is that the profile of neutron monitor data varies depending on the solar magnetic state [11, 12]. The field lines of the Sun's magnetic field impose particular characteristics on the interplanetary field during different solar polarities. Cosmic ray particles typically revolve around the solar system's magnetic field lines. Nonetheless, these field lines are perpendicular to efficient transport. An electron or antiproton are examples of negatively charged particles that drift in the opposite direction of positively charged particles. The particle's drift direction changes in tandem with the reversal of solar polarity. The current sheet is not a one-dimensional plane in practical application; particle motion is extremely complicated. This sheet's wavy structure affects the particle's path across the heliosphere. The behaviour of the solar environment during (a) North-seeking solar polarity and (b) South-seeking solar polarity is shown in Figure 2.

4. Terrestrial cosmic ray flux and atmospheric interactions

It is still unclear how much Earth's cloud cover is impacted by changes in solar activity. There is a widespread belief that the Sun has a major effect on Earth's atmospheric fluctuations because solar radiation intensity only slightly changes during a solar cycle [14]. Nonetheless, studies suggest that the Sun's modulation of the terrestrial cosmic ray flux (CRF) is a major solar effect that should be taken into account as a possible cause of climate change [15, 16]. Because the CRF produces ions that change the electrical conductivity of the atmosphere, it is regarded as a probable factor. This theory is supported by correlations between ice-rafted glacial debris and changes in ^{14}C and ^{10}Be accumulation rates. Such phenomena, observed in the North Atlantic, may contribute to global climate shifts. Observational findings further support the theory that the Sun-modulated CRF affects atmospheric electricity. This interaction, in effect,

sets off an amplification mechanism through which the Sun's role on Earth's ambient conditions gets magnified [17].

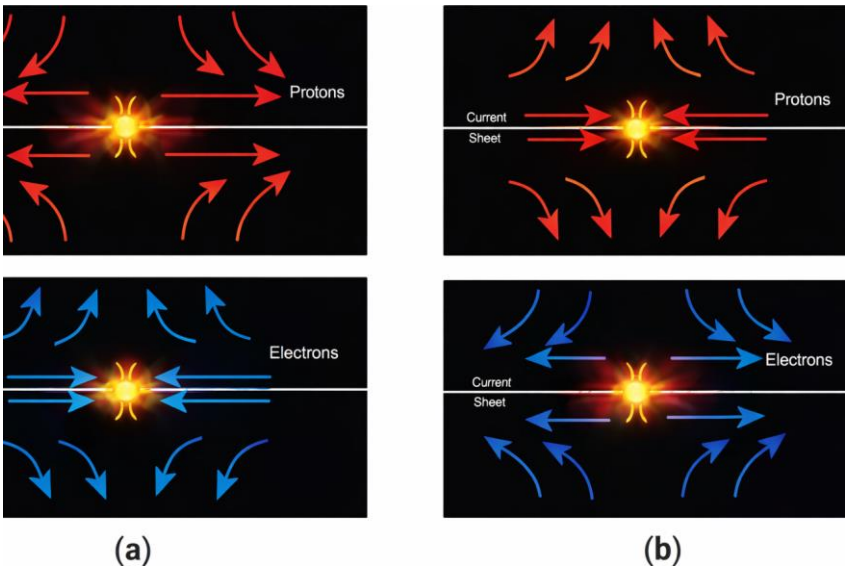


Fig.2. North-Seeking Solar Polarity (+ve) (b) South-Seeking Solar Polarity (-ve)

5. CRF-induced Modulation of Cloud Microphysics

Changes in high-energy particles, viz. cosmic rays, have received much attention from the scientific community, being considered either as a good indicator of solar irradiance or as a direct cause of climate change. Whatever the atmosphere is actually reacting to - the CRF, ultraviolet levels, or total solar irradiance - a significant "amplification" process must be invoked to explain the effects observed [18, 19]. Of these, the influence of CRF on cloud formation offers a more compelling explanation, even though a clear amplification mechanism for irradiance itself has not yet been identified. Dickinson, for instance, proposed that the extent of high-altitude cloud cover is altered by ion-mediated nucleation of sulfate aerosols [20], and similar ion-mediated nucleation has since been reported for sulfate and other aerosol species as well [21]. It is worthy to note, however, that this cosmic-ray-cloud hypothesis remains scientifically debated: controlled aerosol-chamber experiments at CERN's CLOUD facility have found that ion-induced nucleation, though measurable, is generally too small under present-day atmospheric conditions to produce the rise in cloud condensation nuclei needed to explain the variability actually observed in Earth's radiative budget [22]. Consequently, the magnitude of any CRF-driven climate effect remains an open and actively contested question rather than an established mechanism. It is nonetheless evident from analysis of the global electric circuit that the downward flow of vertical electric current density (Jz) is controlled by atmospheric temperature, pressure, and cloud dynamics, and that the solar-modulated CRF is a leading candidate for the main controller of this current. The concentration of cloud condensation nuclei (CCN) and the way ice forms in clouds are both affected by changes in the CRF, and precipitation patterns are, in turn, altered by these microscopic modifications [23]. The CRF thus offers a plausible physical connection between solar activity and Earth's environment by modifying the internal physics of clouds. Changes in Jz are statistically significantly correlated with meteorological responses, according to evidence from diurnal time scales, and cloud coverage over 11-year solar cycles is probably influenced by a similar process. However, a single model cannot easily explain these shifts, because cloud categories respond differently depending on their specific altitude and temperature; evaluating global mean effects therefore requires a more sophisticated, multi-layered modelling framework to account for these atmospheric variations.

6. Couplings Between Solar Activity and Terrestrial Climate

The Sun is a ball of gas and plasma (not a solid object like Earth); it does not rotate as one solid piece, with the equator rotating fastest (about 25 days for one full turn) and the poles rotating much more slowly. Figure 3 shows how different parts of the Sun's surface rotate at different speeds. At high latitudes and during glacial periods, a reduction in solar activity seems to be most effective. Ice-forming nuclei (IFN) were readily accessible during these periods owing to the atmosphere's high dust load [24].

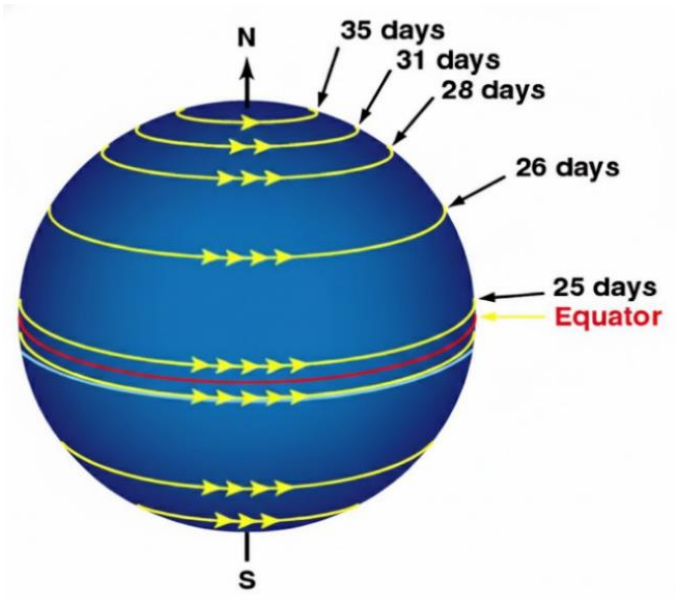


Fig.3. Surface differential rotation of the Sun (adapted from publicly available solar-cycle data [5])

Studies confirm that most nuclei in snow are composed of clays, which function as highly effective IFN, suggesting that the terrestrial cosmic ray flux (CRF) is an important mediator of the Sun-weather relationship [25, 26]. These findings, taken together, point towards the need for a more detailed investigation of how CRF variations influence the vertical current density (Jz) and the microphysical processes associated with it in the atmosphere. Incorporating such responses into suitable cloud-modelling frameworks will, in fact, be essential for a complete description of the global climate system.

This chain of influence is summarized in the block diagram of Figure 4: as solar activity rises, cosmic ray flux is suppressed, which in turn brings down the air-earth current, contact nucleation and precipitation, and correspondingly raises atmospheric dust loading.

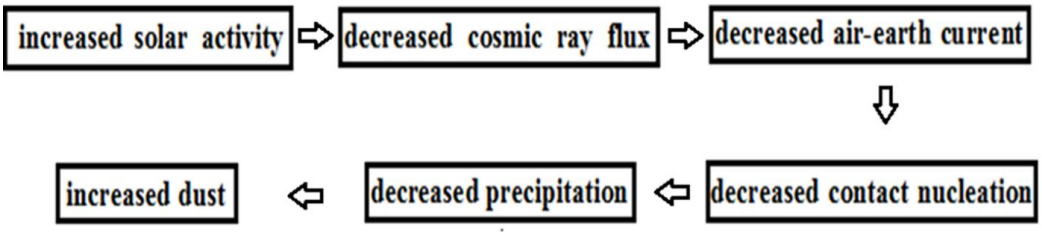


Fig.4. The connection between heightened solar activity and increased atmospheric dust

Long-term trends have been evaluated in Figure 5, which plots the variation of daily sunspot numbers (blue) and monthly sunspot numbers (red) over a 200-year period, viz. 1818 to 2020, reproduced from the NASA Marshall Space Flight Center solar-cycle archive for the purpose of illustrative comparison [27]. Figure 6, in addition, correlates the sunspot number with the open solar magnetic flux, reproduced from Solar and Heliospheric Observatory (SOHO) public data [28]. Cross-correlation of the sunspot series with neutron

monitor count rates indicates that cosmic ray intensity minima typically lag sunspot maxima by approximately 6 to 12 months, consistent with previously reported delay estimates of roughly 6 to 16 months that vary with solar-cycle phase and magnetic polarity [12, 16]. Figure 6 thus highlights the observed time difference between cosmic ray intensity and solar fluctuations, providing insight into the modulation delay within the heliosphere.

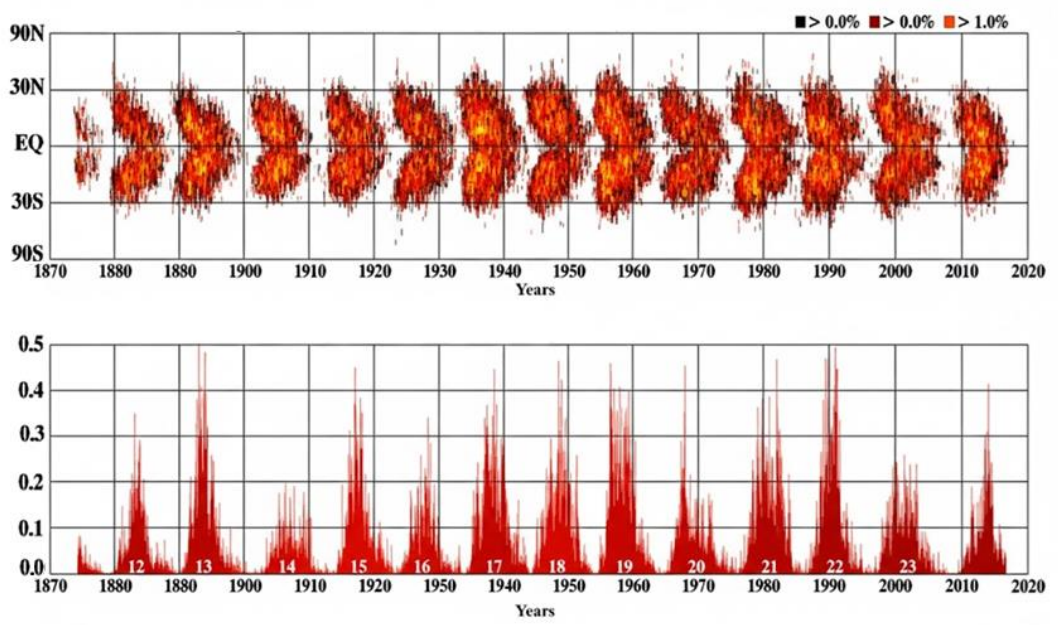


Fig.5. Periodic sunspot numbers for the last 150 years (data source: NASA Marshall Space Flight Center [27])

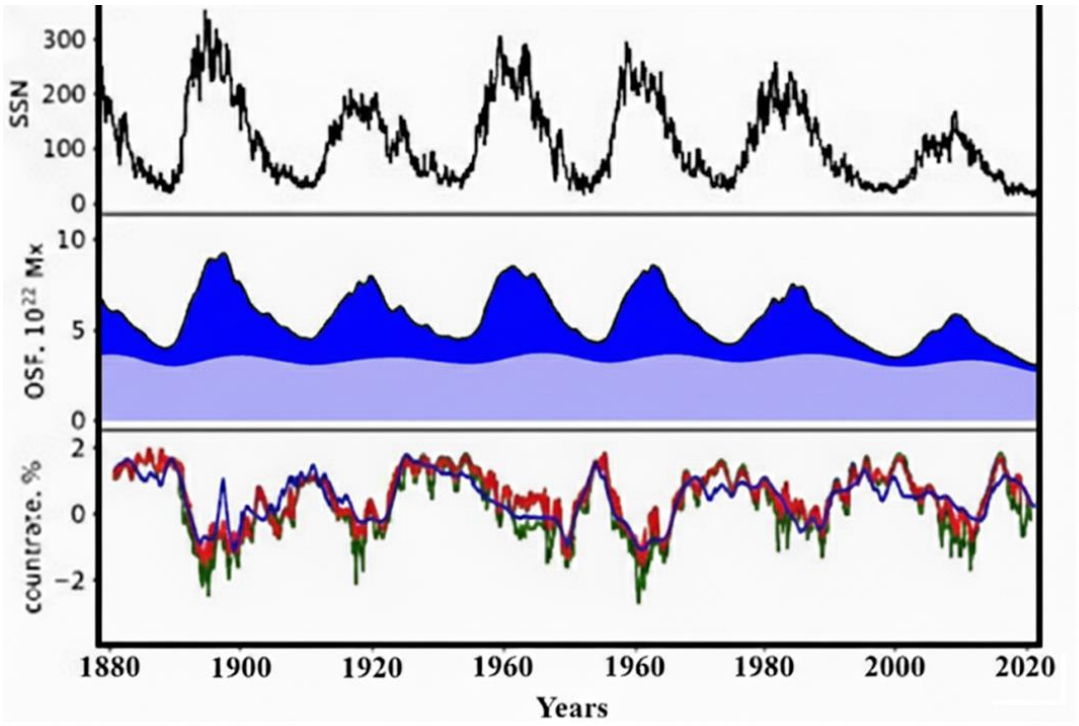


Fig.6. Sunspot number and open solar magnetic flux with time, and observed cosmic ray and solar variability (data source: Solar and Heliospheric Observatory [28])

7. Sunspot Number Variability on Long-Term Global Surface Temperature (GST)

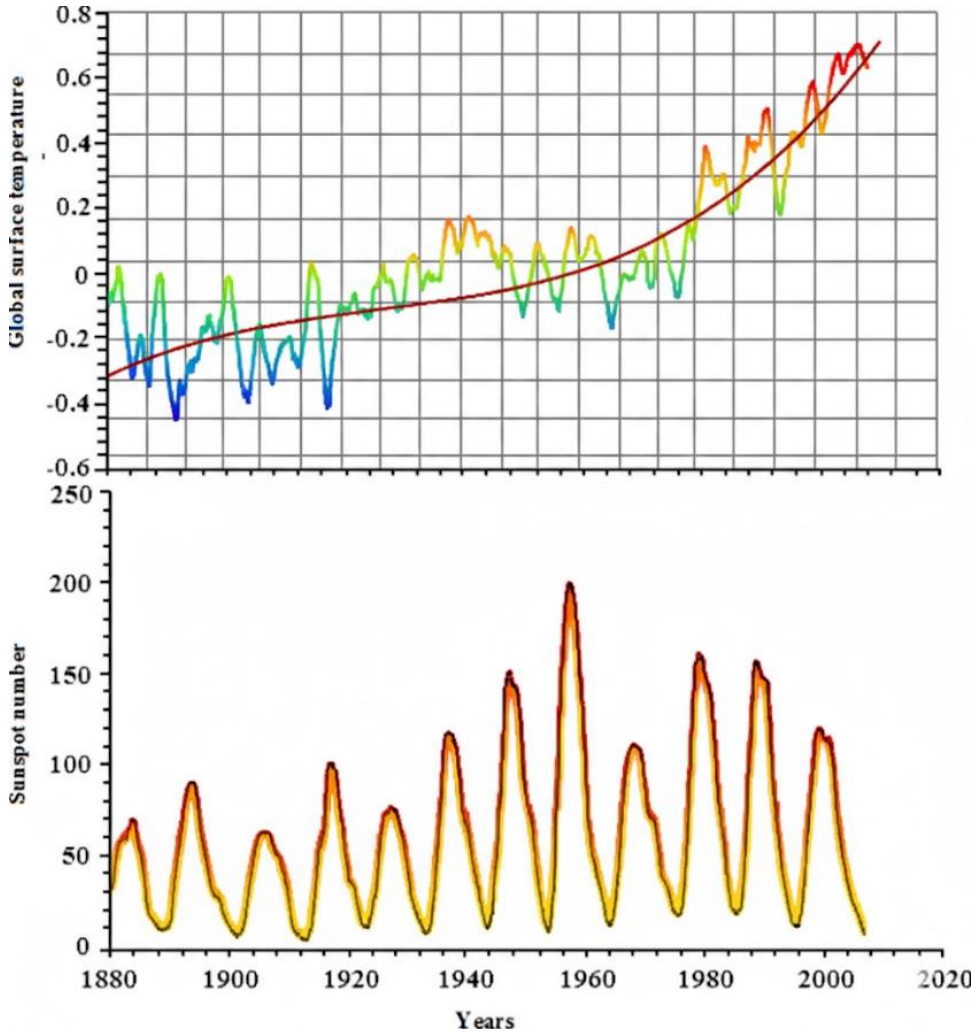


Fig.7. GST and the variation of sunspot numbers over the years (temperature data adapted from Berkeley Earth / IPCC AR6 [7, 8]; sunspot data from WDC-SILSO [5])

Global climate patterns and local weather are greatly influenced by the Sun. The climate is fundamentally shaped by any variation in the total solar energy that reaches the Earth. The incoming solar radiation and the long-wave radiation that the Earth emits are precisely balanced under stable atmospheric conditions, and this equilibrium determines the mean temperature of a given region. One important indicator of changes in climate is the measurement of the global surface temperature. Over the past 200 years, there has been a discernible warming of about 0.8 ± 0.18 ºC in the global surface air temperature (Figure 7), consistent with standard instrumental compilations such as the Berkeley Earth record and the IPCC Sixth Assessment Report [7, 8]. Published comparisons of decadally smoothed sunspot number and GST report a positive correlation, with Pearson coefficients on the order of r ≈ 0.5-0.7 for the pre-1980 record [29, 30]. This correlation weakens substantially after approximately 1980, when GST continues to rise while sunspot activity plateaus and then declines - a divergence widely interpreted as evidence that anthropogenic greenhouse-gas forcing has become the dominant driver of recent warming, even as solar variability continues to modulate climate on shorter time scales [7]. Although studies mainly link this warming to increasing greenhouse gas concentrations [25, 26], evidence points to solar variability as a contributing, secondary factor in global temperature fluctuations [3-4, 9-13]. The 11-year cycle, and its bearing on Earth's electromagnetic environment, has remained a focus of scientific investigation over recent decades [29, 30]. This periodic variability, in a broader sense, provides a framework for understanding how solar fluctuations

contribute to global warming through their effect on the energy balance, though without displacing greenhouse-gas forcing as the primary driver of the long-term warming trend.

8. Conclusion

This review has traced the physical chain linking solar activity to Earth's climate: modulation of galactic cosmic ray flux by the heliospheric magnetic field, the resulting changes in atmospheric ionization and electrical conductivity, and their proposed - but not fully confirmed - influence on cloud condensation nuclei and cloud cover. The evidence for a cosmic-ray-cloud amplification mechanism remains mixed: correlations between CRF, ice-rafted debris, and cosmogenic isotopes support a role for solar-modulated cosmic rays, yet CLOUD-facility experiments indicate that the resulting aerosol nucleation is generally too weak on its own to account for the full observed variability in Earth's radiative budget. Set against this, the sunspot-GST correlation reported here ($r \approx 0.5$-0.7 before 1980) weakens sharply in the post-1980 record, during which greenhouse-gas forcing has become the dominant driver of global warming; solar-cosmic ray coupling should therefore be understood as a secondary modulator of climate variability rather than a substitute for anthropogenic forcing.

The principal contribution of this work is the consolidation of solar, cosmic ray, and climate datasets into a single comparative framework, together with quantitative estimates - a 6-12 month solar-cosmic ray lag and the pre-/post-1980 correlation contrast - that are not readily available together in a single source in the existing review literature. Its main limitation is that it relies on secondary, published data and correlation-level comparisons rather than an independent statistical re-analysis of the raw time series; a natural next step is a dedicated cross-correlation and regression analysis of the WDC-SILSO, NMDB, and GST records at their original sampling resolution, together with a systematic comparison against CLOUD-experiment nucleation rates. Taken together, the evidence reviewed here suggests that stratospheric solar forcing plays a meaningful, if secondary, role in shaping tropospheric climate mechanisms. Such top-down and bottom-up couplings provide a plausible, though not yet fully quantified, pathway through which comparatively small solar variations could contribute to terrestrial weather patterns, alongside - not instead of - the dominant influence of greenhouse-gas forcing on long-term climate trends.

Acknowledgement

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Nomenclature and abbreviations

GCR – Galactic Cosmic Ray

CRF – (Terrestrial) Cosmic Ray Flux

GST – Global Surface Temperature

IFN – Ice-Forming Nuclei

CCN – Cloud Condensation Nuclei

Jz – Vertical (air-earth) electric current density

UV – Ultraviolet radiation

OSF – Open Solar (magnetic) Flux

SSN – Sunspot Number

nT, G – nanotesla, Gauss (units of magnetic field strength)

MeV – Mega electron-volt (unit of particle kinetic energy)

WDC-SILSO – World Data Center for the Sunspot Index and Long-term Solar Observations

NMDB – Neutron Monitor Database

SOHO – Solar and Heliospheric Observatory

IPCC AR6 – Intergovernmental Panel on Climate Change, Sixth Assessment Report

References

[1] I. G. Usoskin. A history of solar activity over millennia. Living Reviews in Solar Physics. 2017; 14(1):3. DOI: 10.1007/s41116-017-0006-9.

[2] M. Lockwood, M. J. Owens, L. A. Barnard. Centennial variations in sunspot number, open solar flux, and streamer belt width: 3. Modeling. Journal of Geophysical Research: Space Physics. 2016; 121(4):3433-3453.

[3] K. Mursula, L. Holappa, I. G. Usoskin. Solar cycle evolution of the solar wind speed distribution. Journal of Geophysical Research: Space Physics. 2015; 120(11):9391-9409.

[4] M. S. Potgieter. Solar modulation of cosmic rays. Living Reviews in Solar Physics. 2013; 10(3).

[5] WDC-SILSO, Royal Observatory of Belgium. Sunspot Number and Long-term Solar Observations. Retrieved from https://www.sidc.be/SILSO/; Accessed 26 Jul 2026.

[6] Neutron Monitor Database (NMDB). Retrieved from https://www.nmdb.eu; Accessed 26 Jul 2026.

[7] IPCC. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2021.

[8] R. A. Rohde, Z. Hausfather. The Berkeley Earth Land/Ocean Temperature Record. Earth System Science Data. 2020; 12:3469-3479.

[9] G. A. Kovaltsov, I. G. Usoskin, E. A. Mironova. Cosmic ray induced ionization in the atmosphere: Spatial and temporal changes. Journal of Geophysical Research: Atmospheres. 2014; 119(20):12061-12073.

[10] N. A. Krivova, S. K. Solanki, Y. C. Unruh. Modeling solar irradiance variability from magnetograms. Journal of Atmospheric and Solar-Terrestrial Physics. 2018; 176:29-35.

[11] H. Svensmark, J. Olaf Pedersen, N. D. Marsh, M. B. Enghoff, U. I. Uggerhøj. Increased ionization supports growth of aerosols into cloud condensation nuclei. Nature Communications. 2017; 8:2199.

[12] M. Lockwood. Solar influence on global and regional climates. Surveys in Geophysics. 2012; 33(3-4):503-534.

[13] E. A. Mironova, et al. Energetic particle influence on the Earth’s atmosphere. Space Science Reviews. 2015; 194:1-96. DOI: 10.1007/s11214-015-0185-4.

[14] L. Gray, et al. Solar influences on climate. Reviews of Geophysics. 2010; 48:RG4001.

[15] M. Owens, M. Lockwood, L. Barnard. The Sun’s role in long-term climate change. Nature Geoscience. 2017; 10(8):559-564. DOI: 10.1038/ngeo2983.

[16] I. G. Usoskin, G. A. Kovaltsov, K. Mursula. Solar activity cycles and their effects on cosmic ray modulation. Journal of Geophysical Research: Space Physics. 2020; 125(6):e2019JA027761.

[17] E. A. Mironova, I. A. Mironov, G. A. Kovaltsov, I. G. Usoskin. Atmospheric ionization response to solar energetic particle events. Journal of Atmospheric and Solar-Terrestrial Physics. 2019; 193:105059.

[18] H. Sarkar, A. Banerjee, A. Bhattacharya, G. Das. Solar modulation of the terrestrial atmosphere and the associated climatic changes. IEEE. 2018:43-50.

[19] J. L. Lean. Estimating solar irradiance since 850 CE. Earth and Space Science. 2018; 5(4):133-149. DOI: 10.1002/2017EA000357.

[20] A. Asvestari, I. G. Usoskin, G. A. Kovaltsov, J. Beer, M. Korte. Past solar activity reconstructed from cosmogenic radionuclides. Astronomy & Astrophysics. 2017; 599:A117. DOI: 10.1051/0004-6361/201629404.

[21] F. Yu, R. P. Turco. Ultrafine aerosol formation via ion-mediated nucleation. Geophysical Research Letters. 2000; 27(6):883-886.

[22] J. Kirkby, et al. Role of sulphuric acid, ammonia and galactic cosmic rays in atmospheric aerosol nucleation. Nature. 2011; 476:429-433.

[23] M. Herbst, K. Kopp, M. Heber. Solar modulation of galactic cosmic rays: Effects of solar cycle 24. Annales Geophysicae. 2017; 35(4):869-878.

[24] Solar Cycle Science. Solar Cycle Science. Retrieved from https://solarcyclescience.com/solarcycle.html; Accessed 26 Jul 2026.

[25] R. G. Harrison. Cloud formation and the possible significance of charge for atmospheric condensation and ice nuclei. Space Science Reviews. 2000; 94(1):381-396. DOI: 10.1023/A:1026708415235.

[26] W. J. R. Alexander. Linkages between solar activity and climatic responses. Energy & Environment. 2005; 16(2):239-253.

[27] NASA Marshall Space Flight Center. Solar Cycle Progression. Retrieved from https://solarscience.msfc.nasa.gov/SunspotCycle.shtml; Accessed 26 Jul 2026.

[28] SOHO Consortium, ESA & NASA. Solar and Heliospheric Observatory Data Archive. Retrieved from https://sohowww.nascom.nasa.gov; Accessed 26 Jul 2026.

[29] J. A. Eddy. Climate and the role of the Sun. In: R. I. Rotberg, T. K. Rabb, editors. Climate and History. Princeton, NJ: Princeton University Press; 1981: 145-167.

[30] E. Friis-Christensen, K. Lassen. Length of the solar cycle, an indication of solar activity closely associated with climate. Science. 1991; 254:698-700.