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Abstract—Solar variability is a natural component of the Earth–Sun system and provides a measurable external source of atmospheric variability. Its contribution to regional climate, however, is difficult to distinguish from internal atmospheric variability and anthropogenic forcing. The present study examines the temporal relationship among solar activity, rainfall and temperature over Bengaluru, India, using the 2005–2020 period for the principal regional analysis and longer records for climatic context. Solar-flux observations from 2004–2024 show the characteristic approximately 11-year solar-cycle modulation, including the weak maximum of Solar Cycle 24 and the subsequent rise of Solar Cycle 25. Annual solar-flux values for 2005–2020 peak around 2014, whereas rainfall exhibits substantial interannual variability without a statistically significant monotonic trend ($Z = 0.4809$, $p = 0.6306$). Temperature shows a contrasting statistically significant increasing trend ($Z = 4.0963$, $p < 0.001$), while solar flux has no significant monotonic trend ($Z = 0.0550$, $p = 0.6778$). The contrasting temporal behaviour indicates that the observed regional warming cannot be attributed simply to a secular increase in solar activity. The rainfall record shows periods of enhanced and reduced variability occurring across different phases of the solar cycle, providing scope for further investigation of possible lagged solar–rainfall coupling. The results emphasise the need to distinguish solar-cycle variability from regional hydroclimatic variability and longer-term warming. The findings have broader relevance to climate resilience, particularly in relation to water security, resilient urban development and climate action under SDGs 6, 11 and 13.

Keywords: *solar variability; solar radio flux; rainfall variability; Bengaluru; monsoon rainfall; temperature variability; solar–atmospheric coupling ; climate resilience*

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1. Introduction

Solar radiation is the main external source of energy for the Earth system and controls the radiative energy available to the atmosphere, land surface and oceans. It plays an important role in atmospheric circulation, surface temperature and the hydrological cycle. Solar activity varies over different time scales, from short-duration eruptive events to the approximately 11-year solar cycle and longer-term variations. The response of the terrestrial atmosphere to these variations is an important subject in solar–terrestrial and atmospheric physics because the solar signal is superimposed on natural variability within the climate system and on anthropogenic forcing [1], [2], [3]. Examination of solar variability together with atmospheric observations may therefore provide useful information on the interaction between external solar forcing and the terrestrial atmosphere.

The approximately 11-year solar cycle is associated with a small but measurable variation in total solar irradiance (TSI). Satellite observations and solar irradiance reconstructions show that the radiative output of the Sun varies with the magnetic activity of the solar surface [4]. The amplitude of TSI variation over a solar cycle is of the order of 0.1%, which is relatively small compared with the radiative forcing associated with the long-term increase in anthropogenic greenhouse gases [3], [5]. Nevertheless, solar variability represents a well-defined natural variation in the external energy input to the Earth system. Its possible influence on the atmosphere is not necessarily restricted to changes in total irradiance, since spectral solar variability and solar energetic particles can also contribute to solar–terrestrial coupling [3]. The magnitude of the response at lower atmospheric and regional scales, however, can be influenced by the background atmospheric state and by interactions among several physical processes.

The solar influence on the atmosphere involves processes extending from the solar surface to the upper atmosphere of the Earth. Changes in solar ultraviolet radiation can affect the stratospheric ozone system, while solar energetic particles and associated geomagnetic activity can modify the ionospheric and thermospheric environment. These processes provide possible pathways for coupling between solar variability and

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the terrestrial atmosphere [3]. At the regional climate scale, however, the identification of a solar signal is more difficult because atmospheric circulation, ocean–atmosphere interaction, aerosols, land-surface processes and internal climate variability operate simultaneously. Therefore, a temporal association between a solar index and a regional climate variable can indicate a possibility for further investigation, but does not by itself establish a direct causal relationship.

Among the commonly used solar indices, the 10.7-cm solar radio flux ($F_{10.7}$), expressed in solar flux units (SFU), is particularly useful for monitoring solar activity. The $F_{10.7}$ index is one of the longest and most widely used radio indicators of solar activity and is also used as a proxy for other solar emissions that are more difficult to observe continuously [6], [7]. It is closely associated with solar magnetic activity and follows the broad progression of the solar cycle. In contrast, TSI represents the integrated radiative energy received at the top of the Earth's atmosphere. The two quantities are therefore related to solar activity but represent different physical observables and should not be treated as interchangeable. This distinction is important when examining possible relationships between solar activity and terrestrial atmospheric variables.

The possible relationship between solar activity and the Indian monsoon has received attention in earlier studies. Bhattacharyya and Narasimha (2005) reported an association between solar activity and Indian monsoon rainfall using long-term rainfall records and several solar indices[8]. Their analysis indicated enhanced rainfall during periods of higher solar activity, although the relationship was not uniform over all periods and rainfall regions. A subsequent regional analysis by Bhattacharyya and Narasimha (2007) showed that the connection between solar activity and Indian monsoon rainfall differs spatially and over different multidecadal periods[9]. These studies indicate that the solar–monsoon relationship may depend on regional atmospheric conditions and the time scale considered. Such findings provide a useful background for examining solar activity and rainfall at a regional location in southern India.

Rainfall over India shows substantial spatial and temporal variability, with the Indian summer monsoon contributing a major part of annual rainfall over large parts of the country. Long-term studies have reported changes in rainfall and temperature at annual, seasonal and regional scales, while extreme rainfall events can contribute significantly to flood risk [11], [12]. The rainfall system is controlled by large-scale circulation, land–ocean thermal contrast, moisture transport, convection and regional atmospheric processes. Consequently, rainfall variability over a particular location cannot normally be explained by a single external forcing. At the same time, comparison of long-term rainfall observations with an independent solar-activity record may help identify possible temporal associations and periods of enhanced or reduced rainfall occurring near different phases of the solar cycle.

Bengaluru provides a useful regional location for such an investigation. The city is situated at an elevation of approximately 920 m and receives rainfall mainly from the southwest monsoon during June–September and from the northeast monsoon during October–November. The local rainfall environment is influenced by seasonal circulation, moisture transport, convective activity and regional topography. In addition, rapid urban development has substantially modified the land-surface characteristics of the Bengaluru urban region. Recent analysis of temperature, rainfall and land-use/land-cover changes over Bengaluru has shown that changes in the built-up environment are associated with modifications in the regional temperature and rainfall characteristics [10]. Such changes are important when interpreting a possible solar signal because urbanisation and land-surface modification can introduce additional variability into local atmospheric observations.

The comparison of solar activity with rainfall and temperature can therefore provide a useful observational framework for examining the behaviour of regional atmospheric variables at different time scales. Short-term atmospheric variability can mask slowly varying signals, whereas monthly and annual averaging may reveal broader variations associated with solar-cycle behaviour and climatic changes. The use of solar-cycle information together with seasonal and annual rainfall and temperature observations may help identify whether any systematic temporal association exists between solar activity and regional atmospheric variability. Such an approach can also help separate cyclic variations associated with solar activity from longer-term changes in terrestrial climate.

The recent solar-flux record provides a useful reference for this purpose. The period from 2004 to 2024 includes the declining phase of Solar Cycle 23, the relatively weak Solar Cycle 24 and the rising phase of Solar Cycle 25. The observed sequence of decreasing, increasing and again decreasing solar activity provides a clear natural cycle against which terrestrial observations can be compared. Examination of the monthly and annual behaviour of $F_{10.7}$ can therefore indicate the dominant solar-cycle structure, while rainfall and temperature records can be examined for corresponding or contrasting temporal behaviour.

The available observations show different characteristics for solar flux, rainfall and temperature. Solar flux exhibits the expected cyclic behaviour associated with solar activity, whereas rainfall shows substantial year-to-year variability without a statistically significant monotonic trend over the analysed period. Temperature, in contrast, shows a statistically significant increasing trend. This difference is important for interpreting solar–climate relationships. A cyclic variation in solar activity should not automatically be interpreted as the cause of a long-term increase in surface temperature. The contrasting behaviour of solar activity and temperature may instead help distinguish solar-cycle variability from the influence of other climate forcings and regional factors. The analysis may therefore contribute to a clearer understanding of what part of the observed regional variability can be associated temporally with solar activity and what part requires consideration of terrestrial processes.

The relationship between solar activity and rainfall is expected to be more complex than a direct one-to-one response. Earlier studies over India have indicated that the association between solar activity and monsoon rainfall can vary with region, period and solar cycle [8],[9]. Possible time lags and the influence of ocean–atmosphere processes may further modify the regional response. Thus, the occurrence of rainfall anomalies during periods of enhanced or reduced solar activity may indicate a possible association rather than direct evidence of solar forcing. Examination of the temporal structure of solar flux and rainfall may nevertheless help to identify patterns that can be investigated further using longer records and additional atmospheric and oceanic parameters.

Rainfall variability is also important from the point of view of climate resilience. Changes in rainfall amount, timing and intensity can influence water availability, agriculture, urban drainage and ecosystem conditions. For Bengaluru, understanding the changing rainfall environment is particularly relevant because the city experiences both periods of water stress and episodes of intense rainfall. Atmospheric observations that improve understanding of rainfall variability can therefore contribute to better water management and climate adaptation. In this broader context, the findings have relevance to SDG 6 through water security, SDG 11 through resilient urban development and SDG 13 through climate action. These connections are considered as broader applications of the atmospheric findings rather than as the primary scientific objective of the study.

The present work examines the temporal variability of solar activity, rainfall and temperature using long-term observations for Bengaluru and the surrounding region. The 2004–2024 solar-flux record is used to describe the recent solar-cycle behaviour, while the overlapping 2005–2020 period is considered for comparison of solar activity with rainfall and temperature. A longer summer monsoon rainfall record from 1969–2024 is also examined to place the recent rainfall variability within a broader climatic perspective. The combined analysis may help identify possible temporal relationships between solar activity and regional atmospheric variability, distinguish cyclic solar behaviour from longer-term temperature change, and provide a basis for further investigation of solar–atmospheric coupling over southern India.

2. Study area, data and methodology

2.1 Study area

Bengaluru is located in southern India at approximately 13°N and 77.6°E, with an elevation of about 920 m above mean sea level. The city has a tropical wet-and-dry climatic setting and receives rainfall mainly from the southwest monsoon during June–September and from the northeast monsoon during October–November. The rainfall distribution is influenced by seasonal atmospheric circulation, moisture transport, convection and local surface conditions. The elevation and inland location provide a distinct regional atmospheric environment compared with coastal and low-elevation regions of southern India.

2.2 Data sources and temporal coverage

The analysis uses solar, rainfall and temperature observations covering different time periods. The principal comparison of solar activity with regional atmospheric variables is carried out for 2005–2020. The solar-activity record extends from 2004 to 2024, allowing the behaviour of recent solar cycles to be examined. A longer summer monsoon rainfall record from 1969–2024 is also considered to place recent rainfall variability within a broader climatic perspective. A long-term TSI diagnostic extending approximately from 1900 to 2020 is used separately for examining the broad solar-radiation and temperature relationship represented in the supplied data.

Solar activity is represented primarily by the 10.7-cm solar radio flux, $F_{10.7}$, expressed in solar flux units (SFU). The $F_{10.7}$ index is a widely used measure of solar activity and is closely related to the magnetic activity of the Sun [6], [7]. It provides a continuous observational record suitable for identifying the progression of solar minima and maxima. The solar-flux record used here covers the declining phase of Solar Cycle 23, Solar Cycle 24 and the beginning of Solar Cycle 25.

Total solar irradiance is considered separately from the solar-radio-flux record. TSI represents the total solar radiative energy received at the top of the Earth's atmosphere and is expressed in W m^{-2}. Satellite observations have established that TSI varies with the magnetic activity of the solar surface, with the variation over an approximately 11-year cycle being of the order of 0.1% [3], [4]. The distinction between TSI and $F_{10.7}$ is important because broadband radiative irradiance and radio emission are different physical observables. In the present analysis, $F_{10.7}$ is therefore treated as a solar-activity proxy and not as direct solar irradiance at the Earth's surface.

Rainfall and temperature observations are obtained from the India Meteorological Department (IMD). The rainfall record is examined at monthly, seasonal and annual scales. Particular attention is given to the summer monsoon period because of its importance to the regional water cycle. The longer 1969–2024 rainfall series is used to examine the broader behaviour of summer monsoon rainfall, while the 2005–2020 record is used for the detailed comparison with solar activity.

2.3 Data preprocessing

The available observations were first examined for temporal consistency and missing values. The supplied methodology uses linear interpolation for isolated missing observations. Such interpolation is appropriate only for short gaps where the surrounding observations provide a reasonable representation of the missing value. Long or continuous data gaps are not assumed to be recovered by interpolation alone.

Standardisation is used when comparison of anomalies between variables is required. For an observation X_t, the standardised anomaly is expressed as

$$z_t = \frac{X_t - \overline{X}}{\sigma_X}, \tag{1}$$

where $\overline{X}$ is the mean of the selected reference period and σ_X is its standard deviation.

Solar-flux anomalies are calculated relative to the selected long-term reference mean. The reference period should correspond to the actual solar dataset used in the final analysis; the term "40-year mean" is therefore not retained unless the underlying 40-year reference dataset is confirmed.

The observations are aggregated into monthly, seasonal and annual values to examine behaviour at different time scales. Seasonal analysis is useful for separating pre-monsoon, southwest monsoon and post-monsoon behaviour. Monthly data are retained because short-term variability may contain information that is lost in annual averages.

Rainfall extremes are identified using percentile-based thresholds. Values at or above the 95th percentile are considered unusually wet conditions, while values at or below the 5th percentile represent unusually dry conditions. These percentile definitions provide a relative measure of rainfall extremes within the selected record and are not interpreted as fixed hydrological flood or drought thresholds.

2.4 Solar-cycle and rainfall comparison

The temporal behaviour of the solar-flux series is first examined to identify the major solar-cycle phases. Monthly solar-flux observations provide information on short-term fluctuations, while annual averaging provides a smoother representation of the approximately 11-year solar cycle. The comparison with rainfall is made using the common period for which the relevant datasets are available.

The solar cycle provides a quasi-periodic external signal, whereas rainfall over Bengaluru is influenced by several atmospheric and oceanic processes and does not necessarily follow a regular periodic pattern. Earlier studies have reported possible relationships between solar activity and Indian monsoon rainfall, but have also indicated regional and multidecadal differences in the strength of the relationship [8], [9]. The present analysis therefore examines temporal correspondence rather than assuming a direct solar control of rainfall.

Particular attention is given to the relative timing of solar maxima, solar minima and rainfall anomalies. A rainfall maximum occurring during a solar-active period may indicate temporal association, while a delayed rainfall response may indicate the possibility of a lagged relationship. Such observations require further physical investigation because Indian monsoon rainfall is also affected by ocean–atmosphere coupling, circulation variability and other climate forcings.

2.5 Correlation and regression analysis

Pearson correlation is used to examine the linear association between pairs of variables. For two variables X and Y, the Pearson correlation coefficient is given by

$$r = \frac{\sum_{i=1}^{n}(X_i - \overline{X})(Y_i - \overline{Y})}{\left[\sum_{i=1}^{n}(X_i - \overline{X})^2 \sum_{i=1}^{n}(Y_i - \overline{Y})^2\right]^{1/2}}. \tag{2}$$

The value of r describes the strength and direction of linear association between the two variables. Statistical significance is considered separately from the magnitude of the correlation because a correlation coefficient alone does not establish physical causation.

Linear regression is used to examine the temporal tendency of the variables. A simple linear model can be expressed as

$$Y = a + bX, \tag{3}$$

where a is the intercept and b is the regression coefficient. For a time-series trend, the independent variable represents time, allowing the sign and magnitude of the slope to indicate an increasing or decreasing tendency.

The statistical trend results supplied with the study indicate that solar flux does not show a significant monotonic trend, with $Z = 0.055$ and $p = 0.6778$. Rainfall also does not show a statistically significant monotonic trend, with $Z = 0.4809$ and $p = 0.6306$. Temperature, in contrast, shows a strong increasing trend, with $Z = 4.0963$ and $p < 0.001$. These results are considered together with the solar-cycle behaviour rather than interpreted as evidence for a direct solar control of regional temperature.

Table 1: Principal variables, temporal coverage and their role in the analysis.

Variable	Period	Role in the analysis
Total solar irradiance (TSI)	~1900–2020	Long-term solar-radiation diagnostic and comparison with the supplied temperature relationship.
Solar flux ($F_{10.7}$)	2004–2024	Solar-activity proxy used to identify solar-cycle phases and short-term variations.
Monthly solar flux	2005–2020	Examination of month-to-month solar-activity variability and solar-cycle evolution.
Annual solar flux	2005–2020	Smoothed representation of the longer-term solar-cycle behaviour.
Rainfall	2005–2020	Comparison of regional rainfall variability with solar activity.
Summer monsoon rainfall	1969–2024	Longer-term assessment of monsoon rainfall variability and extreme years.
Temperature	Multi-year record	Assessment of the long-term thermal behaviour of the region.

2.6 Periodic analysis

Wavelet analysis is considered for investigating periodic variations and possible time-dependent relationships between solar activity and rainfall. Wavelet analysis can be useful for atmospheric time series because dominant periodicities may change with time. It can therefore help distinguish a persistent solar-cycle signal from short-lived or intermittent periodic behaviour. Numerical wavelet coefficients are not reported here because the corresponding numerical outputs were not included in the supplied results.

2.7 TSI–temperature radiative diagnostic

A separate TSI–temperature diagnostic supplied with the study shows a nearly exact linear relationship between the plotted quantities, with Pearson's $r = 1$ and adjusted $R^2 = 1$. The temperature represented in this diagnostic is close to 254.6 K, and the fitted relationship is

$$T = 190.94684 + 0.04676\,\mathrm{TSI}. \tag{4}$$

The physical interpretation of this result requires particular care. A perfect correlation is not normally expected between independently observed TSI and surface temperature because the terrestrial climate system contains many internal and external processes. If the temperature values in the diagnostic were calculated from TSI through a radiative-equilibrium or related transformation, the near-perfect correlation follows from the mathematical construction of the variables and cannot be regarded as an independent observational demonstration of solar control of surface temperature.

Accordingly, the TSI–temperature relationship is treated in this study as a radiative diagnostic rather than as evidence that TSI independently predicts observed surface temperature. The observed regional temperature trend is instead examined separately from solar-cycle variability. This distinction is important for avoiding overinterpretation of the solar contribution to terrestrial climate, particularly because the measured solar-cycle variation in TSI is relatively small compared with the long-term radiative influence of anthropogenic greenhouse gases [3], [5].

2.8 Overall analytical approach

The overall methodology combines solar-cycle analysis, temporal averaging, rainfall anomaly analysis, correlation, regression and trend assessment. Solar-flux observations provide the external solar reference, rainfall represents regional hydrological variability and temperature provides an indicator of the longer-term thermal state.

The analysis is designed primarily to identify temporal associations and contrasting trends. It does not assume that solar activity is the dominant control of Bengaluru rainfall or temperature. The possibility of solar–atmospheric coupling is considered in relation to the known variability of the Indian monsoon and the influence of regional and global climate processes. The results may therefore provide a basis for further investigation using longer observations, additional solar indices, oceanic parameters and atmospheric circulation information.

3. Results

3.1 Long-term total solar irradiance and temperature

Figure 1 shows the long-term variation of total solar irradiance (TSI) and the temperature series supplied with the study over approximately 1900–2020. The TSI record contains repeated variations on the approximately 11-year solar-cycle time scale. The cyclic structure is clearly visible, although the amplitude of the variation is small compared with the mean radiative output of the Sun. This behaviour is consistent with the established solar-cycle variation in irradiance described by Gray et al. (2010) and Yeo et al. (2017) [3], [4].

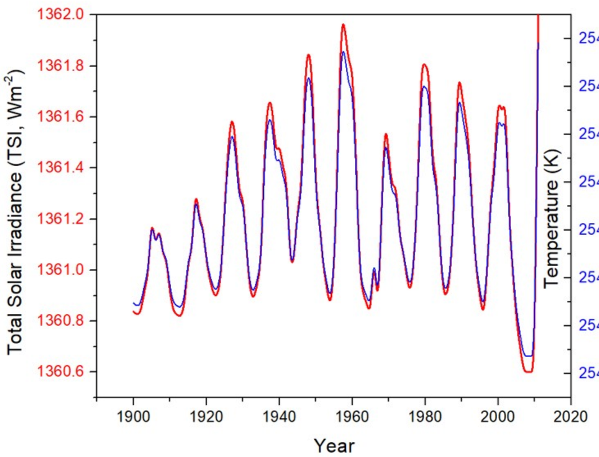

Figure 1: Long-term variation of total solar irradiance (TSI) and the supplied temperature series over approximately 1900–2020. The repeated approximately 11-year structure in TSI represents the solar-cycle variation.

The temperature series in the supplied diagnostic follows the oscillatory pattern of the TSI-related quantity closely. This close correspondence, however, should be interpreted in relation to the construction of the plotted temperature variable. Figure 2 gives a nearly exact linear relationship, with $r = 1$ and adjusted $R^2 = 1$. Such a result is not expected from two independent observations of TSI and surface temperature. The relationship is therefore treated as a radiative diagnostic rather than as an independent observational demonstration of solar control of surface temperature.

When the long-term behaviour is considered beyond the individual solar cycles, the temperature record shows an increasing tendency that is not matched by a comparable secular increase in solar irradiance. This difference is important because the approximately 11-year solar cycle represents a cyclic variation, whereas the observed long-term temperature change contains a secular component. The result is consistent with the interpretation that solar variability forms one part of the Earth–Sun system but cannot by itself account for the recent long-term warming behaviour. Gray et al. (2010) also emphasised the need to distinguish solar variability from other climate forcings when interpreting solar–climate relationships [3].

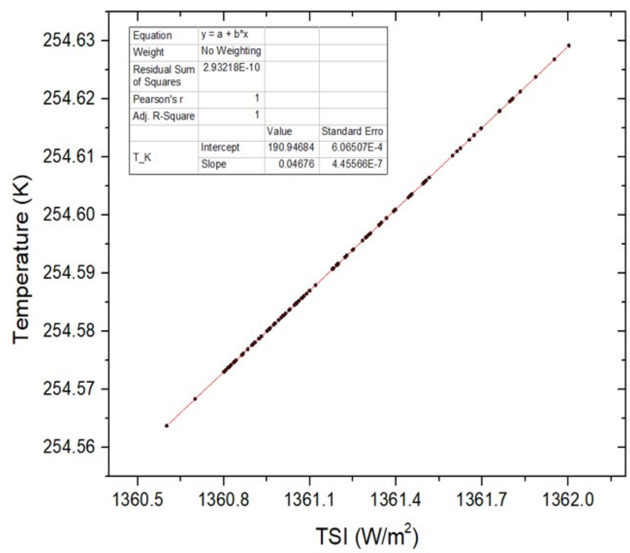

Figure 2: Linear diagnostic between the supplied TSI and temperature variables. The near-perfect fit is treated as a radiative diagnostic and not as an independent observational attribution of surface temperature to TSI.

3.2 Solar-flux variability during 2004–2024

Figure 3 presents the solar-flux record for 2004–2024. The broad envelope shows the expected evolution of recent solar activity. Solar flux decreases from the beginning of the record towards the 2008–2009 solar minimum, increases towards the Solar Cycle 24 maximum around 2013–2014, and subsequently decreases towards the 2019–2020 minimum. A clear increase follows after 2020 with the development of Solar Cycle 25.

The record therefore provides a suitable external solar reference for the regional atmospheric analysis. The relatively weak amplitude of Solar Cycle 24 is also visible in comparison with the stronger increase associated with Solar Cycle 25. Short-duration excursions are superposed on the smoother cycle envelope. These excursions represent shorter-timescale solar variability and should not be interpreted directly as a rainfall-forcing signal. Tapping (1987, 2013) established the value of the 10.7-cm radio flux as a long-term indicator of solar activity, making the observed cycle structure physically useful for the present comparison [6], [7].

3.3 Monthly and annual solar-flux behaviour

The monthly solar-flux record for 2005–2020 is shown in Figure 4. The monthly series contains substantial short-term variability, but the underlying solar-cycle envelope remains clear. The record begins during the declining phase of Solar Cycle 23, reaches the relatively broad maximum of Solar Cycle 24 around 2013–2014 and then declines towards the Solar Cycle 24/25 minimum.

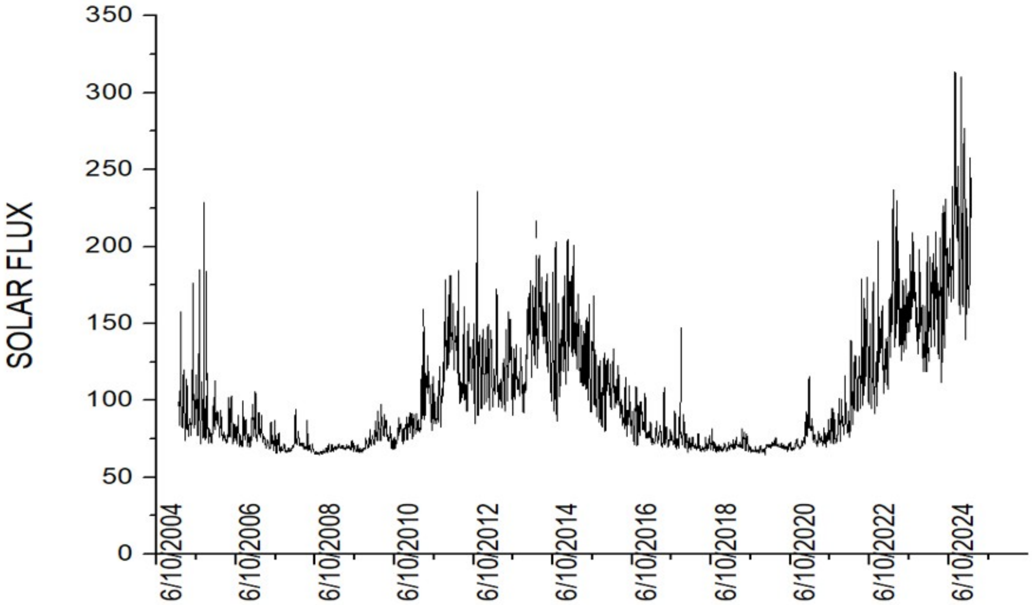

Figure 3: Solar-flux variability from 2004 to 2024. The broad envelope represents solar-cycle modulation, while shorter excursions indicate higher-frequency solar variability.

Annual averaging substantially reduces the short-duration variability. Figure 5 shows the minimum around 2008–2009, the subsequent increase towards 2014, and the decline through 2019. The rise during 2020 marks the beginning of the new solar-cycle phase. The annual series is therefore more suitable than the monthly series for comparison with annual or seasonal climate quantities when the objective is to examine solar-cycle-scale behaviour.

The difference between Figures 4 and 5 is important for the interpretation of possible solar–atmospheric coupling. A regional atmospheric response, if present, may not follow every short-lived solar excursion. A comparison at annual or seasonal scales can reduce high-frequency solar variability, while monthly analysis can retain possible shorter-period or lagged behaviour.

3.4 Temperature variability and long-term tendency

The temperature observations show substantially different behaviour from the solar-flux record. Daily temperature contains considerable short-period weather variability, while monthly averaging produces a smoother series and reveals a persistent increasing tendency. The supplied monthly linear fit has a slope of approximately 0.0124 °C per time unit and an intercept of approximately 24.327 °C, with $R^2 = 0.4704$.

The value of R^2 indicates that the fitted temporal tendency explains only part of the observed temperature variability. The remaining variability is consistent with the influence of atmospheric circulation, cloudiness, monsoon conditions, aerosols, land-surface processes and other components of regional climate variability. The difference between daily variability and the monthly trend also demonstrates why a comparison between a weak externally varying solar signal and regional temperature requires an appropriate time scale.

The trend statistics provide stronger evidence for the direction of the temperature change. The reported temperature trend has $Z = 4.0963$ and $p < 0.001$, indicating a statistically significant increasing tendency. In contrast, the solar-flux series has no statistically significant monotonic trend. The temperature increase therefore cannot be represented simply as a response to a secular increase in solar activity.

3.5 Rainfall variability in relation to solar-cycle phase

The comparison of solar flux and rainfall over 2005–2020 shows a clear difference in temporal organisation. Solar flux follows a comparatively regular solar-cycle pattern, whereas rainfall varies strongly from year to year. The rainfall series contains periods of relatively high and low rainfall and does not reproduce the smooth solar-cycle envelope.

Some rainfall anomalies occur with a temporal displacement from the solar maximum. Such displacement is potentially interesting because a response of the lower atmosphere to solar variability, if physically present, need not be instantaneous. A delayed relationship could involve intermediate processes in atmospheric circulation or ocean–atmosphere coupling. However, visual temporal displacement alone cannot establish a solar influence. The rainfall response over southern India is af-

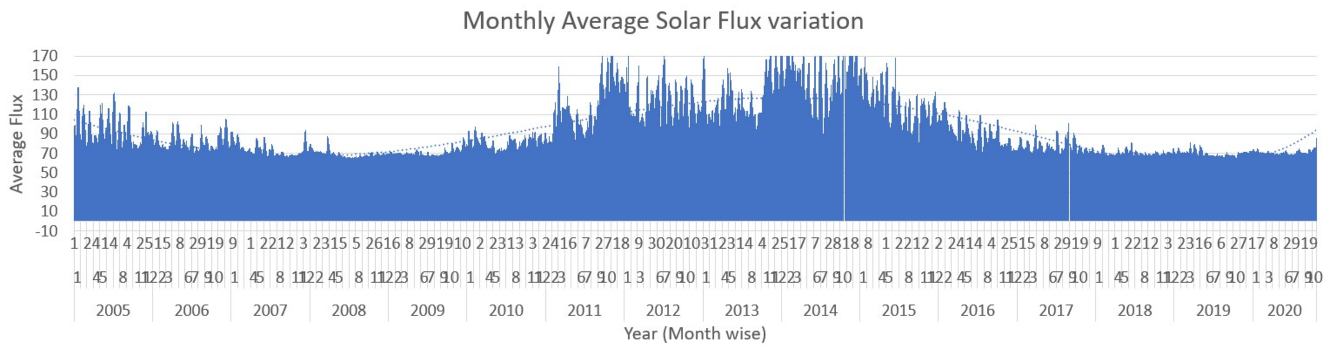

Figure 4: Monthly average solar flux from 2005 to 2020. Short-timescale variations are superposed on the longer solar-cycle envelope.

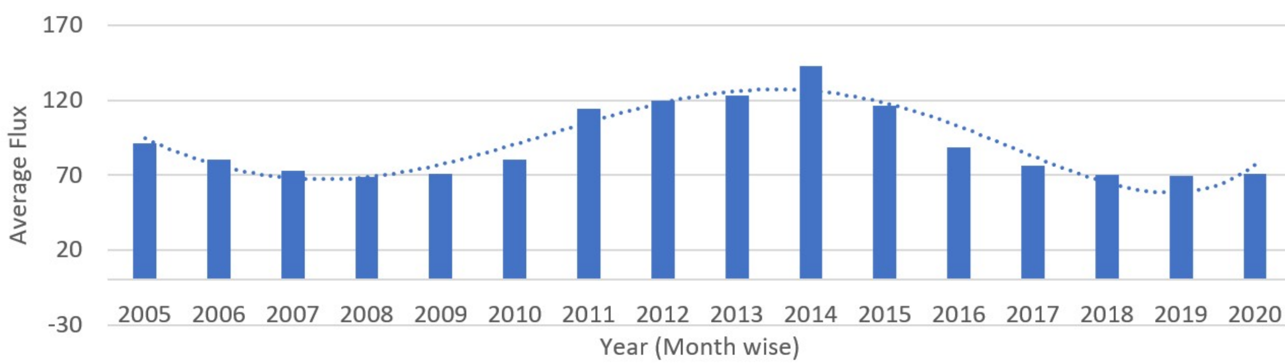

Figure 5: Annual average solar flux from 2005 to 2020. Annual averaging emphasises the solar-cycle evolution and suppresses short-lived variations.

fected by monsoon circulation, moisture transport and oceanic boundary conditions, and the solar signal may be small relative to this internal variability.

Earlier Indian studies provide a useful comparison. Bhattacharyya and Narasimha (2005) reported an association between solar activity and Indian monsoon rainfall, while Bhattacharyya and Narasimha (2007) showed that such connections can differ between regions and over different multidecadal periods. The present Bengaluru observations are therefore best considered as a regional contribution to this broader question rather than as evidence of a uniform solar control of Indian rainfall [8], [9].

3.6 Long-term summer monsoon rainfall

Figure 6 presents the summer monsoon rainfall (SMR) record for 1969–2024. The record contains large interannual departures from the long-term behaviour, with prominent high-rainfall years around 1988, 1998, 2017 and 2023. These departures demonstrate the large natural variability of the Indian monsoon system.

The polynomial fit provides a visual description of the broad variation but does not by itself establish a physical trend or forcing mechanism. In particular, an apparent change in the fitted curve after approximately 2015 should not be interpreted as evidence of a solar origin. Monsoon rainfall is controlled by several interacting processes, including land–ocean thermal contrast, large-scale circulation, sea-surface temperature variability, moisture transport and coupled ocean–atmosphere modes. Guhathakurta et al. (2011) also demonstrated the importance of extreme rainfall variability in the Indian climate system [11].

The long rainfall record is nevertheless important in the present study because it places the shorter 2005–2020 solar–rainfall comparison within a broader hydroclimatic background. The large amplitude of interannual rainfall variability provides an indication of the difficulty of detecting a relatively small external solar signal in a regional rainfall record.

3.7 Trend statistics of solar flux, rainfall and temperature

The reported trend statistics provide a direct comparison of the three main variables, as summarised in Table 2. Solar flux has $Z = 0.0550$ and $p = 0.6778$, indicating no statistically significant monotonic trend. Rainfall has $Z = 0.4809$

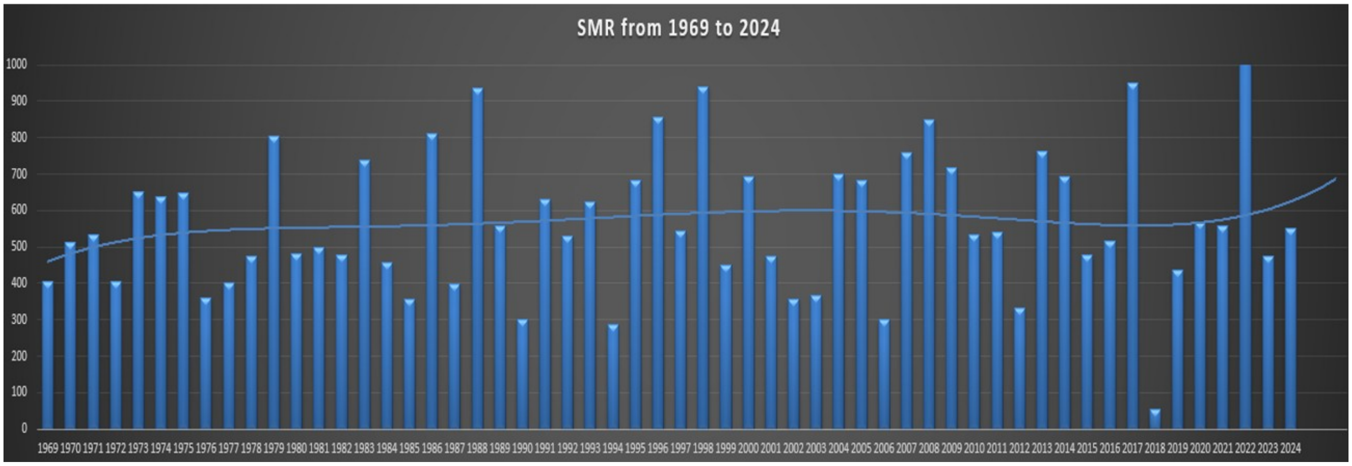

Figure 6: Summer monsoon rainfall from 1969 to 2024 with the supplied polynomial fit. Large interannual excursions illustrate the variability of the Indian monsoon rainfall regime.

and p = 0.6306, also indicating no statistically significant monotonic trend. Temperature has $Z = 4.0963$ and $p < 0.001$, demonstrating a statistically significant increasing trend.

This contrast is an important result of the study. Solar activity retains a clear cyclic structure but does not show a significant monotonic increase over the analysed period. Rainfall also lacks a significant monotonic trend, although substantial year-to-year variability is evident. Temperature, in contrast, exhibits a distinct long-term increasing tendency. The three variables therefore show different temporal characteristics: solar flux provides a cyclic external reference, rainfall represents highly variable regional hydroclimatic behaviour, and temperature shows a longer-term warming signal.

4. Discussion

4.1 Solar variability as an external atmospheric signal

The results show a distinct difference between the temporal behaviour of solar activity and the regional atmospheric variables over Bengaluru. The solar-flux record retains the characteristic approximately 11-year solar-cycle variation, with the declining phase of Solar Cycle 23, the relatively weak Solar Cycle 24 and the rising phase of Solar Cycle 25 clearly represented in Figure 3. The monthly and annual records in Figures 4 and 5 further show that short-term fluctuations are superimposed on a broader solar-cycle envelope. Such variability is consistent with the established changes in solar magnetic activity and solar irradiance over the solar cycle [2], G[3], [4]).

The absence of a statistically significant monotonic trend in solar flux is also important. A solar cycle is fundamentally a periodic or quasi-periodic variation and should not be expected to appear as a persistent linear increase or decrease over a relatively short interval. The non-significant solar trend therefore does not indicate an absence of solar variability. Instead, it indicates that the dominant behaviour of the solar-flux record is cyclic rather than secular. This distinction is important when comparing solar activity with regional climate variables that may contain both short-term variability and longer-term trends [3].

Solar variability can influence the terrestrial environment through changes in irradiance and through indirect pathways involving the upper atmosphere and atmospheric chemistry (Reid, 2000; [3]. Changes in solar irradiance are closely associated with magnetic activity on the solar surface, and the observed irradiance variability can be reproduced from the evolving solar magnetic features [4]. The transfer of a relatively small solar signal into regional lower-atmospheric variability, however, is not expected to be straightforward. Atmospheric circulation, cloud processes, ocean–atmosphere coupling and other terrestrial processes can modify or mask such a signal. The Bengaluru observations therefore provide a useful regional setting for examining the possibility of solar–atmospheric coupling without assuming that solar variability is the dominant control of the observed climate variables.

4.2 Solar activity and rainfall variability

The rainfall record does not reproduce the regular solar-cycle structure seen in the solar-flux series. Instead, substantial year-to-year variability is observed over Bengaluru, with wet and dry periods occurring within different phases of the solar cycle. This difference is physically reasonable because rainfall is a response of a dynamically coupled atmospheric system rather than a direct radiative measurement. The Indian monsoon involves large-scale circulation, moisture transport, land–ocean thermal contrast and convection, with additional modulation from oceanic and regional atmospheric processes [11], [12].

Table 2: Reported trend statistics for solar flux, rainfall and temperature.

Variable	Z	p	Significance	Interpretation
Solar flux	0.0550	0.6778	Not significant	No monotonic trend detected
Rainfall	0.4809	0.6306	Not significant	No monotonic trend detected
Temperature	4.0963	< 0.001	Significant	Increasing trend

Earlier investigations have reported possible relationships between solar activity and Indian monsoon rainfall. Bhattacharyya and Narasimha (2005) reported an association between solar activity and Indian monsoon rainfall, while Bhattacharyya and Narasimha (2007) showed that such connections can differ between regions and over different multidecadal periods [8], [9]. These findings are important for the present study because they indicate that any solar influence on rainfall is unlikely to be spatially uniform. The rainfall behaviour over Bengaluru may therefore represent a regional response within a larger monsoon system rather than a direct response to the solar cycle.

Some rainfall anomalies occur near or with an apparent temporal displacement from phases of enhanced or reduced solar activity. Such behaviour may be of interest for investigating a possible lagged solar–atmospheric response. Earlier wavelet-based work on Indian monsoon rainfall has also reported power near the approximately 11-year solar-cycle period, although the strength and persistence of such relationships have varied with the record and region [8], [9]. A delayed response could involve intermediate atmospheric or ocean–atmosphere processes rather than an immediate radiative response. However, the present observations do not provide sufficient evidence to assign a causal interpretation to these temporal associations. The observed correspondence is therefore better regarded as a possibility that can be tested using longer records and more detailed lagged and time-frequency analyses.

The absence of a statistically significant monotonic rainfall trend ($Z = 0.4809$, $p = 0.6306$) also needs to be distinguished from the absence of rainfall variability. The long-term summer monsoon record in Figure 6 contains substantial interannual departures, including years with markedly enhanced or reduced rainfall. Long-term analyses of Indian rainfall have similarly shown substantial spatial and temporal variability in rainfall and temperature [11], [12]. Thus, the rainfall system can remain highly variable even when a simple monotonic trend is not detected.

4.3 Importance of distinguishing $F_{10.7}$, TSI and surface radiation

The interpretation of the solar results depends on maintaining a clear distinction between $F_{10.7}$ and TSI. The 10.7-cm solar radio flux is a radio-frequency indicator of solar activity and is expressed in solar flux units, whereas TSI represents the integrated solar radiative energy received at the top of the Earth's atmosphere and is expressed in $\mathrm{W\,m^{-2}}$. The long observational record and established physical interpretation of $F_{10.7}$ make it a useful indicator of solar magnetic activity [6], [7]. TSI, in contrast, provides the appropriate quantity for considering changes in the total radiative energy input from the Sun [2], [3].

An increase in $F_{10.7}$ should therefore not be interpreted as an equivalent increase in surface solar heating. Radiation reaching the Earth's surface is modified by atmospheric absorption and scattering, cloud cover, water vapour, aerosols and solar geometry. This distinction is particularly important when relating a solar index to rainfall. The physically relevant question is whether changes in solar activity may be associated with atmospheric circulation or other processes that influence the hydrological cycle, rather than whether SFU directly represents the energy received at the Bengaluru surface [3].

4.4 Temperature trend and solar-cycle variability

The temperature record shows a behaviour distinctly different from the solar-flux record. The temperature trend is statistically significant ($Z = 4.0963$, $p < 0.001$), whereas solar flux does not show a significant monotonic trend. The temperature increase therefore cannot be interpreted simply as a consequence of a secular increase in solar activity. This distinction is consistent with the broader physical assessment that recent global warming cannot be explained by solar variability alone and that human influence is the dominant driver of the observed long-term warming of the atmosphere, ocean and land [5].

The regional temperature record can contain contributions from several processes, including large-scale atmospheric circulation, cloudiness, aerosols and changes in land-surface conditions. Recent observations for Bengaluru have reported changes in temperature and rainfall together with land-use and land-cover changes [10]. Such findings provide an important regional context for the present temperature result. The current analysis does not quantify the separate contribution of these processes, and the temperature result is therefore interpreted as an observed regional warming tendency rather than as a single-forcing attribution.

4.5 Interpretation of the TSI–temperature diagnostic

The TSI–temperature relationship shown in Figure 2 requires a separate interpretation from the observed regional temperature trend. The diagnostic gives $r = 1$ and adjusted $R^2 = 1$, together with the fitted relationship

$$T = 190.94684 + 0.04676\,\mathrm{TSI}. \quad (5)$$

The approximately 11-year variation in TSI is a real solar signal, with solar-cycle changes in irradiance linked to magnetic activity on the solar surface [3], [4]. However, a perfect linear correspondence between TSI and temperature would require strong physical justification if both quantities were independently observed.

If the temperature values in this diagnostic were calculated from TSI through a radiative-equilibrium or related transformation, the perfect correlation follows from the mathematical construction of the quantities. In that case, the relationship is useful for demonstrating the radiative connection represented by the model, but it cannot be considered an independent observational test of solar control of surface temperature.

This distinction prevents the long-term TSI diagnostic from being confused with the regional temperature trend. The measured solar-cycle variation is physically real, but its magnitude and pathway of influence on regional climate must be considered together with other external and internal climate forcings [3], [5].

4.6 Long-term rainfall variability and regional hydroclimate

The 1969–2024 summer monsoon rainfall record provides a longer perspective on rainfall behaviour than the 2005–2020 solar–rainfall comparison. Figure 6 shows substantial interannual variability, with several years departing strongly from the long-term rainfall behaviour. Such variability is characteristic of the Indian monsoon system and is important for understanding regional water availability [11], [12].

The absence of a statistically significant monotonic trend should therefore not be interpreted as climatic stability. A rainfall series may have little linear trend while still experiencing substantial changes in the frequency, timing or intensity of individual rainfall events. The percentile-based approach used in the present analysis provides a simple way of identifying unusually wet and dry conditions. More detailed assessment of rainfall extremes would require event duration, intensity, antecedent rainfall and hydrological response to be considered together, as rainfall extremes can have a disproportionate effect on regional flood risk [11].

For Bengaluru, this distinction has direct atmospheric and societal importance. Water availability depends on the seasonal distribution of rainfall, while urban flooding is strongly influenced by short-duration intense rainfall. Consequently, annual rainfall totals alone cannot fully represent hydroclimatic risk. The long rainfall record and the shorter solar–rainfall comparison together provide a useful basis for separating background monsoon variability from possible external modulation.

4.7 Regional atmospheric significance

The combined observations indicate that Bengaluru rainfall and temperature form part of a multi-process atmospheric system in which solar variability represents one possible external component. The Indian monsoon establishes the dominant seasonal background, while ocean–atmosphere interaction, regional circulation, convection and moisture transport contribute to interannual variability [11], [12]. Local atmospheric and surface processes further modify the observed response.

This interpretation avoids two extreme possibilities. A lack of a strong solar–rainfall correlation should not automatically be taken as proof that solar variability has no atmospheric relevance. Conversely, a temporal coincidence between a rainfall anomaly and a solar maximum should not be treated as evidence of direct solar forcing. Earlier Indian studies themselves indicate that solar–monsoon relationships can be regional and time-dependent [8], [9]. The present observations therefore support a cautious interpretation in which solar variability provides a measurable external periodic reference and the regional atmospheric response is examined within the much larger variability of the monsoon system.

The contrasting trends provide additional support for this interpretation. Solar flux shows cyclic variability without a significant monotonic trend, rainfall shows substantial interannual variability without a significant monotonic trend, and temperature shows a statistically significant increasing tendency. The three records therefore contain different temporal signatures, which is useful for distinguishing solar-cycle variability from longer-term regional climate change [3], [5].

4.8 Climate resilience and broader relevance

The atmospheric results have practical relevance for climate resilience in Bengaluru because rainfall variability and increasing temperature influence water availability, urban drainage, heat exposure and ecosystem conditions. The absence of a significant monotonic rainfall trend does not remove the need for resilience planning because individual high-rainfall events can still produce substantial impacts. The broader evidence for changes in temperature and climate extremes also supports the need to consider adaptation at regional and urban scales [5].

The findings have broader relevance to SDG 6 through water security, SDG 11 through resilient urban development and SDG 13 through climate action. The connection is primarily application-oriented rather than a separate objective of the study. Improved understanding of rainfall variability can support seasonal water planning and rainfall-risk assessment, while the observed temperature tendency provides additional motivation for heat-resilience measures. The atmospheric analysis therefore contributes indirectly to sustainable development by improving the physical understanding needed for regional adaptation.

4.9 Implications for solar–atmospheric research

The present results suggest that the solar–rainfall relationship over Bengaluru requires analysis at more than one time scale. Annual averaging is useful for identifying solar-cycle modulation, whereas monthly data may retain information about shorter-period variability and possible lagged responses. Earlier solar–monsoon studies have used spectral and wavelet approaches to investigate common periodicities, demonstrating the value of time-frequency analysis for this problem [8], [9].

A longer and more homogeneous observational record would provide a stronger basis for such analysis. Additional solar indices, atmospheric circulation parameters and major oceanic modes such as ENSO and the Indian Ocean Dipole could help distinguish a possible solar contribution from established sources of monsoon variability. Such an approach may determine whether the temporal associations identified in the present study represent a reproducible solar–atmospheric signal or arise primarily from internal climate variability.

The finding is the contrasting temporal behaviour of solar activity, rainfall and temperature. Solar activity retains a clear approximately 11-year cyclic structure, rainfall exhibits strong interannual variability without a statistically significant monotonic trend, and temperature shows a statistically significant increasing tendency. This combination provides a useful observational framework for examining the relationship between solar variability and regional atmospheric behaviour.

The findings do not establish direct solar control of Bengaluru rainfall or temperature. Rather, they indicate that solar activity provides a physically meaningful external reference against which regional atmospheric variability can be examined. The comparison may help address a regional observational gap by bringing solar-cycle behaviour, rainfall variability and temperature change into a common atmospheric-physics framework for southern India. Further observations and physically based lagged and time-frequency analyses can strengthen the assessment of whether the identified associations contain a reproducible solar contribution.

5. Conclusions

A multi-timescale analysis of solar activity, rainfall and temperature over Bengaluru provides a clear distinction between cyclic solar variability and the irregular behaviour of regional hydroclimate. The solar-flux record for 2004–2024 shows the characteristic approximately 11-year solar-cycle modulation, including the minimum around 2008–2009, the maximum around 2013–2014 and the subsequent increase associated with Solar Cycle 25. Annual averaging over 2005–2020 provides a clearer representation of the solar-cycle behaviour, while the monthly record retains substantial short-timescale variability. This behaviour is consistent with the established solar-cycle variability reported by Lean (2005) and Gray et al. (2010) [2], [3].

The rainfall record shows substantial interannual variability but no statistically significant monotonic trend in the reported analysis ($Z = 0.4809$, $p = 0.6306$). The longer summer monsoon rainfall record further illustrates the large natural variability of the Indian monsoon system. Such variability is important even in the absence of a significant long-term linear trend because the timing and intensity of individual rainfall events can have major regional consequences [11], [12]. The rainfall behaviour therefore does not reproduce the regular solar-cycle pattern and cannot be interpreted as a simple direct response to solar activity.

Temperature shows a contrasting behaviour, with a statistically significant increasing trend ($Z = 4.0963$, $p < 0.001$), while solar flux does not show a statistically significant monotonic trend ($Z = 0.0550$, $p = 0.6778$). This difference indicates that the observed regional temperature increase cannot be explained simply by a secular increase in solar activity. The result is consistent with the broader understanding that recent long-term warming involves forcings and processes beyond solar-cycle variability [3], [5]. The regional temperature record may also contain the effects of atmospheric circulation, aerosols, cloudiness and changing surface conditions, which are not separately quantified in the present analysis.

The study provides a cautious basis for considering possible solar–rainfall coupling over southern India. Earlier studies have reported possible associations between solar activity and Indian monsoon rainfall, while also indicating regional and multidecadal differences in the strength of the relationship [8], [9]. The present results similarly indicate that any solar-related rainfall response, if present, is unlikely to be a simple one-to-one relationship. The comparison of solar activity with rainfall may therefore help identify periods or time scales requiring further investigation, particularly through lagged and time-frequency analysis. A causal solar influence should not be inferred from visual correspondence or simple correlation alone.

The distinction between $F_{10.7}$ and TSI is also important for the physical interpretation of the results. The $F_{10.7}$ record provides a solar-activity reference, whereas TSI represents the total radiative energy received at the top of the atmosphere [6], [7], [4]. The near-perfect TSI–temperature diagnostic is therefore treated as a radiative diagnostic and not as an independent observational attribution of surface temperature to solar irradiance.

From a climate-resilience perspective, the most relevant finding is that the absence of a statistically significant rainfall trend does not imply the absence of hydroclimatic risk. Substantial rainfall variability, intense events and the observed temperature increase remain important for water availability, urban drainage and heat exposure in Bengaluru. The findings therefore have broader relevance to SDG 6 on water security, SDG 11 on resilient cities and SDG 13 on climate action. These connections provide an application context for the atmospheric results without replacing physical analysis with policy interpretation.

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Data availability

The study uses solar-activity, solar-irradiance, rainfall and temperature datasets obtained from established observational and scientific data resources. Solar activity and $F_{10.7}$ observations are available through the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information and associated solar-terrestrial data services. Total solar irradiance and related solar-irradiance products are available through NASA solar-irradiance data resources. Rainfall and temperature observations for India are available through the India Meteorological Department (IMD) and its associated meteorological data services.

The datasets used in the analysis can be accessed through the respective official web resources, subject to the data-access and usage provisions of the data providers. Specific dataset identifiers, station information, retrieval dates and quality-control details will be provided in the final submitted version where applicable.

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