

Temporal and scale-dependent associations of Lagos rainfall with Solar and Geomagnetic activity (1995-2024)

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Abstract: *This study investigated the non-stationary relationships between rainfall variability and solar-geomagnetic activity over Lagos, Nigeria, during 1995-2024, using monthly rainfall, F10.7 solar radio flux, and geomagnetic aa-index data. Deseasonalised anomalies were analysed using 60- and 120-month rolling Spearman correlations, AR(1) surrogate significance tests, false discovery rate (FDR) correction, and Morlet wavelet coherence. Rainfall-F10.7 correlations exhibited significant temporal variability, with maximum absolute coefficients of 0.482 and 0.355 for the respective windows. Both timescales yielded globally significant associations ($p = 0.0305$ and $p = 0.0120$, respectively), although only the 120-month analysis identified FDR-significant windows, predominantly around 2002-2004. Conversely, rainfall-aa correlations were weaker and statistically insignificant at both timescales. Wavelet coherence revealed intermittent, pointwise significant rainfall-F10.7 associations, particularly at 18-26-month and 40-55-month periods, alongside localised rainfall-aa coherence at selected timescales. These findings demonstrate that solar radio flux exhibits a more statistically robust, but temporally variable, association with Lagos rainfall than geomagnetic activity. The results underscore the importance of time-resolved statistical approaches in solar-terrestrial climate investigations while supporting a cautious interpretation of non-stationary associations rather than causal solar control of Lagos rainfall.*

Keywords: Deseasonalisation; radio flux; geomagnetic index; rolling Spearman correlation; wavelet coherence.

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1.0 Introduction

Rainfall variability over coastal southwestern Nigeria is shaped by the West African monsoon, the seasonal migration of tropical rain belts, Atlantic moisture transport, and interactions among regional and large-scale circulation processes. Its pronounced seasonality, including the mid-season reduction in coastal rainfall, makes Lagos a useful setting for testing whether associations with external solar and geophysical forcing persist after the annual cycle has been removed. Nicholson (2013) emphasised the complex, multiscale nature of West African monsoon variability; her synthesis provides an essential climatic context but does not establish solar forcing of Lagos rainfall.

Possible links between solar activity and precipitation have attracted attention for decades. Klaus (1978), examining West African station rainfall and phases of sunspot activity during 1921-1973, reported phase-related regional precipitation anomalies. Such historical findings motivate renewed investigation, but they cannot be transferred directly to contemporary climate variability, period and solar indicators. Solar radio flux at 10.7 cm is a standard indicator of solar activity; geomagnetic aa quantifies global magnetic disturbance and is not interchangeable with F10.7. Mechanisms connecting either index to tropical rainfall are subject to ongoing research and debate, and observed statistical associations can arise from internal climate variability, shared trends, chance, or indirect pathways (Ibanga *et al.*, 2024). Published results on the link of climate variability to solar and geomagnetic activity in West Africa in general and Nigeria

in particular are many and varied, and provide an important basis for the present investigation. Okeke and Audu (2017) analysed observations from 15 Nigerian stations and compared rainfall and temperature with sunspot numbers and the geomagnetic aa index. Their conventional correlations with solar-geomagnetic indices were not statistically significant, although spectral peaks suggested shared periodicities. Such coincident periods do not, by themselves, demonstrate a physical solar influence on rainfall. Hanson and Okeke (2021) reported negligible relationships between solar-geomagnetic activity and rainfall and temperature variability in the wet zone of West Africa, suggesting that solar and geomagnetic influences play a relatively minor role in the region's climate variability. However, the findings tend to warrant further investigation into the possible nonlinear, time-varying and frequency-dependent relationships between solar-geomagnetic activity and rainfall variability, using different statistical and time-frequency techniques to identify potential associations that conventional correlation and regression analyses may not adequately capture.

Of particular interest and relevance to this study are results that point to the need to decouple the seasonal influences from those that may arise from solar and geomagnetic forcing. For instance, Ugbeji and Okpala (2020) emphasised the variable August break and the role of tropical circulation systems, while Falaiye, Ijila and Abimbola (2021) explored seasonal meteorological variability in Nigerian stations relative to solar activity. Ugwu and Ugonabo (2024a) examined Nigerian precipitation from 1902 to 2021 using sunspot numbers and F10.7, reporting generally weak and season-dependent associations. In a related analysis using CRU gridded rainfall, Ugwu and Ugonabo (2024b) likewise found weak correlations in most seasons and stronger negative tendencies for dry-season rainfall. Furthermore, Onori et al. (2026) investigated Lagos monthly rainfall

and sunspot numbers during 2002-2012, finding no statistically significant overall relationship and small correlations that differed among solar epochs. The present study extends the time coverage to 1995-2024, uses F10.7 cm radio flux alongside the geomagnetic aa index, and examines time-varying correlations with persistence-aware significance tests rather than treating one full-period coefficient as representative.

These studies and findings underscore the need to remove the monthly climatology and to avoid attributing rainfall variability to solar forcing without controlling for monsoon and ocean-atmosphere influences, and also motivate the present station-specific monthly assessment.

2.0 Data and Sources

The study uses 360 consecutive monthly observations spanning January 1995 to December 2024. Lagos monthly rainfall totals (mm) were supplied as a 12-month-by-30-year NiMet station table. All reported zero values were treated as valid zero rainfall rather than missing observations.

Daily F10.7 radio flux was obtained from NASA/GSFC Space Physics Data Facility OMNIWeb and averaged by calendar month. OMNI documentation identifies the daily F10.7 index as adjusted to 1 astronomical unit and expressed in solar flux units ($1 \text{ sfu} = 10^{22} \text{ W m}^2 \text{ Hz}^{-1}$). Three-hourly aa observations were obtained from the International Service of Geomagnetic Indices (ISGI), averaged into monthly means and expressed in nT. The prepared monthly files were aligned by year and month; the final merged series contains no missing monthly records. Data, sources and temporal resolution are summarised in Table 1.

3.0 Methods of Analysis

To ensure temporal consistency among the datasets, the daily solar F10.7 flux and three-hourly geomagnetic aa-index observations were aggregated into monthly means. For each variable, the monthly mean was calculated as the arithmetic average of all



valid observations within the corresponding calendar month, expressed as:

$$\bar{X}(y, m) = \frac{1}{n(y, m)} \sum_{i=1}^{n(y, m)} X_i \quad (1)$$

where $\bar{X}(y, m)$ is the monthly mean of the solar F10.7 flux or geomagnetic aa index; X_i

is the i -th valid observation within the month; $n(y, m)$ is the number of valid observations in month m of year y ; y denotes the year (1995–2024); and m denotes the calendar month (January–December).

Table 1: Summary of Variables, Temporal Resolution, Analysis Variables, and Data Sources

Variable	Lagos rainfall	Solar F10.7 cm radio flux	Geomagnetic aa index
Temporal resolution	Monthly total	Daily values	3-hourly values
Analysis variable	Monthly rainfall total	Monthly mean (sfu)	Monthly mean (nT)
Source	NiMet station observations	NASA OMNIWeb	ISGI

To minimise the influence of the recurring seasonal cycle, monthly anomalies were calculated by subtracting the corresponding long-term calendar-month mean from each observation:

$$X'(y, m) = X(y, m) - \mu X(m) \quad (2)$$

where the long-term monthly climatological mean is given by:

$$\mu X(m) = \frac{1}{N} \sum_{y=1995}^{2024} X(y, m) \quad (3)$$

$X'(y, m)$ represents the monthly anomaly, $X(y, m)$ is the observed monthly value, $\mu X(m)$ is the 30-year climatological mean for calendar month m , and $N = 30$ is the number of years considered.

The anomaly calculation was applied separately to rainfall, solar F10.7 flux and the geomagnetic aa index. This procedure removes the mean seasonal cycle and allows the analysis to focus on departures from normal monthly conditions, thereby reducing the influence of seasonal variations on the estimated statistical relationships. However, deseasonalisation does not remove long-term trends or other low-frequency variability that may be present in the datasets. Spearman's rank correlation coefficient r_s was employed

to assess the strength and direction of the monotonic relationships between monthly rainfall anomalies and the corresponding anomalies of solar F10.7 flux and geomagnetic aa activity. Spearman's correlation is a non-parametric measure that evaluates the association between two variables based on their ranks rather than their original numerical values, making it less sensitive to extreme observations and departures from normality.

The Spearman rank correlation coefficient was calculated as the Pearson correlation coefficient of the ranked observations, expressed as:

$$r_s = \frac{\sum_{i=1}^n (R_i - \bar{R})(S_i - \bar{S})}{\sqrt{\sum_{i=1}^n (R_i - \bar{R})^2 (S_i - \bar{S})^2}} \quad (4)$$

where: r_s is Spearman's rank correlation coefficient; R_i is the rank of the i -th monthly rainfall anomaly; S_i is the rank of the corresponding solar F10.7 or geomagnetic aa anomaly; $\bar{R}$ and $\bar{S}$ are the arithmetic means of their respective ranks; and n is the number of paired monthly observations. Average ranks were assigned to tied observations.

To investigate temporal variations in the relationships, rolling Spearman correlations were calculated using moving windows of 60



months (5 years) and 120 months (10 years). Each window was advanced by one month, and the correlation coefficient was

$$r_s^{(W)}(t) = \text{corr}[\text{rank}(X'_{t:t+W-1}), \text{rank}(Y'_{t:t+W-1})] \quad (5)$$

where: $r_s^{(W)}(t)$ is the rolling Spearman correlation coefficient for the window beginning at month t ; X' represents the monthly rainfall anomaly series; Y' represents the monthly solar F10.7 or geomagnetic aa anomaly series; W is the moving-window length, corresponding to either 60 or 120 consecutive months; t denotes the starting position of the moving window; and corr denotes the Pearson correlation calculated from the ranked observations.

For a complete series containing N monthly observations, the number of rolling correlation estimates is given by:

$$N_W = N - W + 1 \quad (6)$$

where N is the number of moving-window correlation estimates, $N = 360$ is the total number of monthly observations covering January 1995 to December 2024, and W is the selected window length. Consequently, the 60-month and 120-month moving windows yielded 301 and 241 correlation estimates, respectively, for each rainfall-solar and rainfall-geomagnetic relationship. The resulting coefficients range from -1 to +1. Positive values indicate that higher-ranked rainfall anomalies tend to occur with higher-ranked solar or geomagnetic anomalies, whereas negative values indicate an inverse association. Values approaching zero indicate weak monotonic relationships. The moving-window approach therefore enables the identification of periods during which the relationships strengthen, weaken or change direction. However, because successive windows overlap substantially, their correlation estimates are not statistically independent. Furthermore, the observed associations are interpreted as statistical relationships rather than evidence of a causal influence of solar or geomagnetic activity on rainfall variability.

$$Z_t = \phi Z_{t-1} + \varepsilon_t \quad (7)$$

recalculated using the observations contained within that window. The rolling correlation is expressed as:

where Z_t is the simulated anomaly at time t ; Z_{t-1} is the anomaly at the preceding monthly time step; ϕ is the estimated lag-one autoregressive coefficient, representing temporal persistence; and ε_t is a Gaussian random innovation with zero mean and constant variance, σ_ε^2 .

The stationarity condition $\phi < 1$ was imposed. The AR (1) coefficients were estimated separately for each observed anomaly series, allowing the simulated datasets to reproduce their respective short-term persistence characteristics.

For each rainfall-predictor pair, $B = 2,000$ independent surrogate pairs were generated under the null hypothesis of no association between the two variables. The complete 60-month and 120-month rolling Spearman correlation analyses were repeated for each surrogate pair, producing a reference distribution of correlation coefficients for every moving window. The empirical two-sided significance probability for each rolling window was estimated as:

$$p_t = \frac{1 + \sum_{b=1}^B I(|r_{s,t}^{*(b)}| \geq r_{s,t}^{\text{obs}})}{B + 1} \quad (8)$$

where: p_t is the empirical two-sided p-value for the rolling window at position t ; $B = 2,000$ is the number of surrogate simulations; $r_{s,t}^{\text{obs}}$ is the observed rolling Spearman correlation coefficient; $r_{s,t}^{*(b)}$ is the corresponding coefficient obtained from the b -th surrogate pair; and $I(\cdot)$ is an indicator function equal to 1 when the stated condition is satisfied and 0 otherwise.

To evaluate the overall significance of the strongest observed correlation while accounting for the multiple overlapping windows, a global maximum-correlation statistic was calculated as:

$$M_{\text{obs}} = \max_{1 \leq t \leq N_W} |r_{s,t}^{\text{obs}}| \quad (9)$$



where M_{obs} is the largest absolute observed rolling correlation coefficient and N_W is the total number of moving windows.

For each surrogate simulation, the corresponding maximum statistic was calculated as:

$$M^{*(b)} = \max_{1 \leq t \leq N_W} |r_{s,t}^{*(b)}| \quad (10)$$

The empirical global significance probability was then determined from:

$$p_{global} = \frac{\sum_{b=1}^B I(M^{*(b)} \geq M_{obs})}{B + 1} \quad (11)$$

where p_{global} is the probability of obtaining a maximum absolute correlation at least as large as the observed maximum under the AR(1) null hypothesis. A value of $p_{global} < 0.05$ was considered statistically significant at the 95% confidence level.

To further address multiple comparisons among individual rolling windows, the empirical pointwise p-values were adjusted using the Benjamini–Hochberg false discovery rate (FDR) procedure. The ordered p-values were expressed as:

$$p(1) \leq p(2) \leq \dots \leq p(m) \quad (12)$$

The corresponding FDR-adjusted p-values were calculated as:

$$q_{(i)} = \min \left[1, \min_{k=1, \dots, m} \left(\frac{m}{k} p(k) \right) \right] \quad (13)$$

where: $p(i)$ is the i -th smallest empirical p-value; $q_{(i)}$ is its corresponding FDR-adjusted p-value; m is the total number of rolling-window tests (301 for 60-month windows and 241 for 120-month windows); i and k are the ordered p-value indices; and the minimum operator ensures that adjusted p-values do not exceed unity and remain monotonic in their ordered sequence. An FDR-adjusted value of $q < 0.05$ was used to identify individual windows meeting the nominal 5% FDR criterion. However, because successive moving windows overlap substantially, the resulting correlation coefficients and their associated p-values are strongly dependent. Consequently, the FDR-

adjusted equation here results were interpreted cautiously, since the standard Benjamini-Hochberg procedure does not guarantee FDR control under every form of dependence.

Wavelet coherence analysis was employed to investigate the time-dependent and scale-dependent relationships between Lagos rainfall variability and solar–geomagnetic activity during 1995–2024. Unlike conventional correlation analysis, which provides a measure of association over a specified time interval, wavelet coherence identifies periods during which two time series exhibit locally consistent oscillatory behaviour at particular timescales.

The continuous wavelet transform (CWT), based on the Morlet mother wavelet, was applied separately to the deseasonalised monthly rainfall, solar F10.7 flux and geomagnetic aa-index series. The continuous wavelet transforms of a time series $X(t)$ is expressed, after Torrence and Compo (1998) and Grinsted (2004), as:

$$W_X(s, \tau) = \frac{1}{\sqrt{s}} \int_{-\infty}^{+\infty} X(t) \psi^* \left(\frac{t - \tau}{s} \right) dt \quad (14)$$

where $W_X(s, \tau)$ is the continuous wavelet transform of the time series $X(t)$; $X(t)$ represents the deseasonalised monthly rainfall, F10.7 flux or geomagnetic aa-index series; s is the wavelet scale, which is related to the oscillation period; τ is the time-localisation parameter; t denotes time; ψ is the Morlet mother wavelet; and the superscript $*$ denotes complex conjugation. The Morlet mother wavelet is defined as:

$$\psi(\eta) = \pi^{-1/4} e^{i\omega_0 \eta} e^{-\eta^2/2} \quad (15)$$

where η is the dimensionless time parameter, and ω_0 is the dimensionless central angular frequency of the Morlet wavelet.

To quantify the localised association between rainfall and each solar–geomagnetic variable, the squared wavelet coherence was calculated as:



$$R^2(s, \tau) = \frac{|S[s^{-1}W_{XY}(s, \tau)]|^2}{S[s^{-1}|W_X(s, \tau)|^2]S[s^{-1}|W_Y(s, \tau)|^2]} \quad (16)$$

where the cross-wavelet transform is defined by:

$$W_{XY}(s, \tau) = W_X(s, \tau)W_Y^*(s, \tau) \quad (17)$$

In Equations (16) and (17), $R^2(s, \tau)$ is the squared wavelet coherence between two time series at scale s and time τ ; $W_X(s, \tau)$ is the wavelet transform of the rainfall anomaly series; W_Y is the wavelet transform of either the solar F10.7 or geomagnetic aa anomaly series; S denotes a smoothing operator applied in both time and scale; s^{-1} is the inverse wavelet-scale weighting factor; and $|\cdot|^2$ denotes the squared modulus of a complex quantity. The squared wavelet coherence varies between zero and unity. Values approaching unity indicate strong localised coherence between the two time series at the corresponding time and oscillation period, whereas values approaching zero indicate weak coherence.

The analysis considered oscillation periods ranging from 2 to 128 months, allowing the investigation of intraseasonal, annual and interannual associations. However, the longest periods are represented by relatively few complete oscillations within the 30-year observational record and must therefore be interpreted cautiously.

To account for boundary effects associated with the finite length of the time series, the cone of influence (COI) was identified. Regions outside the COI, where edge effects become important, were excluded from the interpretation of reliable coherence patterns. Statistical significance was assessed using Monte Carlo simulations based on independently generated AR(1) surrogate pairs. For each rainfall-predictor relationship, 300 surrogate pairs were generated to reproduce the individual lag-one persistence characteristics of the observed anomaly series while removing their mutual association.

The empirical pointwise significance probability at each time-scale location was estimated as:

$$p(s, \tau) = \frac{\sum_{b=1}^B I[R_b^{2*}(s, \tau) \geq R_{obs}^2(r, \tau)]}{B + 1} \quad (18)$$

where $p(s, \tau)$ is the empirical pointwise significance probability at scale s and time τ ; $B = 300$ is the number of independent surrogate simulations; $R_{obs}^2(r, \tau)$ is the observed squared wavelet coherence; $R_b^{2*}(s, \tau)$ is the squared coherence obtained from the b -th surrogate pair; and $I(\cdot)$ is an indicator function equal to 1 when the stated condition is satisfied and 0 otherwise.

The Morlet continuous wavelet transform $W_x(s, t)$ was used to represent time-dependent oscillatory content. Squared wavelet coherence was estimated as

A pointwise significance level of $p < 0.05$ was adopted to identify regions where the observed coherence exceeded that expected under the AR(1) null hypothesis. However, because significance testing was performed at numerous time-scale locations, the resulting 95% significance regions were considered exploratory rather than globally significant. No fieldwise or clusterwise multiple-testing correction was applied to the wavelet coherence maps. Furthermore, phase-difference arrows were not calculated in the present analysis. Consequently, the wavelet coherence results were interpreted only in terms of the strength, timing and characteristic periods of the observed associations, without making inferences about phase relationships, lead-lag behaviour or causality. This approach complements the rolling Spearman correlation analysis by providing additional information on the temporal localisation and oscillation periods of rainfall-solar and rainfall-geomagnetic associations during the study period.

3.0 Results and Discussion

The mean annual rainfall total over the 30-year period is 1,266.96 mm. Annual totals range from 628.9 mm (2001) to 2,030.1 mm



(2023), highlighting pronounced interannual variability. The monthly climatology is strongly seasonal: June is wettest (244.61 mm), followed by September (200.85 mm), while December (4.64 mm) and January (9.79 mm) are driest. August (73.47 mm) shows a clear reduction between July and September. This pattern is consistent with the well-known complexity of coastal West African monsoon seasonality described in regional syntheses such as Nicholson (2013), although a single-station series cannot characterise the full regional monsoon.

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Fig. 2 presents the 60-month rolling Spearman correlation between rainfall and solar radio flux (F10.7) over Lagos during 1995-2024, together with the corresponding AR(1) surrogate-based significance estimates. The upper panel shows the

observed rolling correlation (black solid line) and pointwise 95% AR(1) surrogate significance limits (red dashed lines).

The lower panel presents the corresponding pointwise p-values (black solid line), Benjamini-Hochberg-adjusted q-values (blue dotted line), and 5% significance threshold (red dashed line). The global maximum-statistic test yields $p = 0.0305$, indicating a statistically significant overall correlation excursion despite the absence of individually FDR-significant windows. The results reveal a pronounced non-stationary relationship, characterised by alternating periods of negative and positive correlations. A relatively strong negative correlation ($r_s \approx -0.45$) occurred during 2003-2004, followed by a transition to predominantly positive correlations after 2006, reaching approximately $r_s = 0.35$ during 2013-2014. The relationship subsequently weakened, becoming temporarily negative around 2017-2018, before recovering to weakly positive values towards the end of the study period. The pointwise significance test ($p < 0.05$) identifies statistically significant negative correlations around 2003-2004 and positive correlations around 2013-2014. However, these intervals do not remain significant following Benjamini-Hochberg false discovery rate (FDR) correction ($q > 0.05$), indicating limited evidence for individually significant correlation windows after accounting for multiple comparisons.

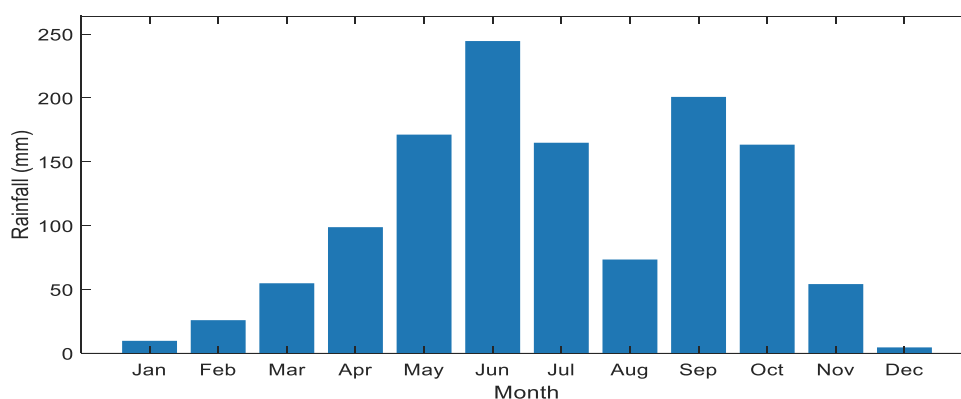


Fig. 1: Lagos monthly rainfall climatology, 1995-2024



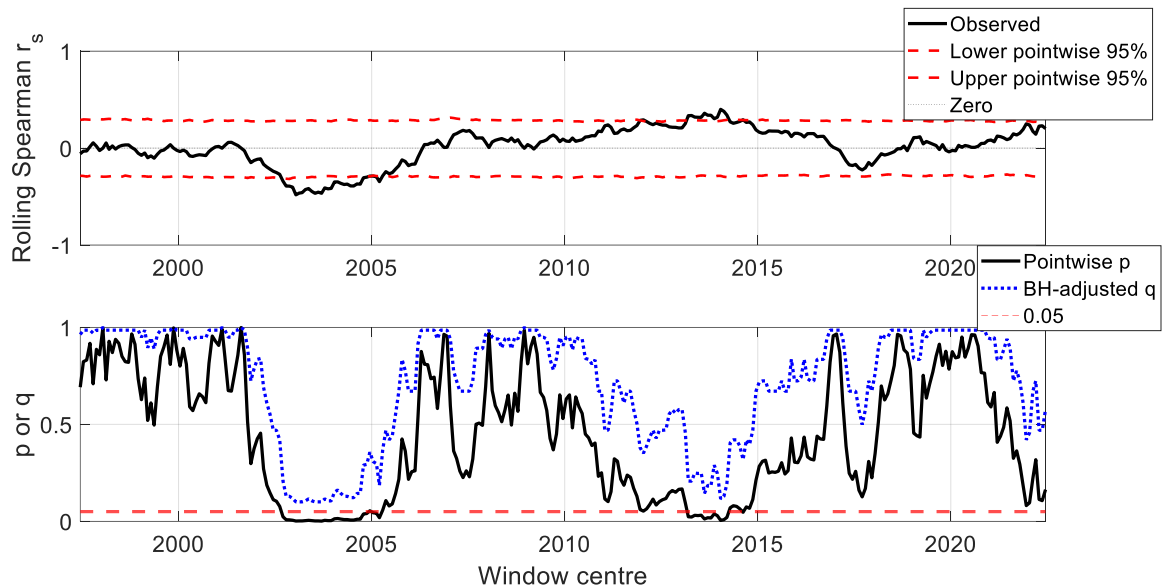


Fig. 2: 60-month rolling Spearman correlation between monthly rainfall anomalies and solar radio flux (F10.7) anomalies over Lagos, Nigeria.

Nevertheless, the global maximum-statistic test ($p = 0.0305$) indicates that the strongest observed correlation excursion is statistically significant at the 5% level under the adopted AR(1) surrogate null model. These findings suggest that the relationship between solar activity and rainfall over Lagos is temporally variable rather than persistent, with changes in both correlation strength and direction. Although the global test provides evidence against the null hypothesis of no association across the entire rolling-correlation sequence, the absence of FDR-significant individual windows warrants caution in attributing specific rainfall variations to solar forcing. The results therefore extend the findings of Hanson and Okeke (2021), who reported negligible overall solar-climate relationships in the wet zone of West Africa, by suggesting that weak long-term associations may coexist with episodic, time-dependent correlations. Fig. 3 shows that the 120-month rolling Spearman correlation between rainfall and F10.7 anomalies over Lagos exhibited marked temporal variability, with predominantly negative correlations during 2000–2007, reaching a maximum absolute correlation of $r_s = 0.355$ around 2003–2004, followed by weak positive correlations

during 2008–2020. The AR(1) surrogate-based global maximum test confirmed a statistically significant correlation excursion ($p = 0.0120$), while Benjamini-Hochberg correction identified 14 statistically significant rolling windows at the 5% false discovery rate. These significant windows were concentrated within the negative correlation episode around 2002–2004.

Compared with the 60-month analysis (Fig. 2), the 120-month correlations exhibited reduced temporal fluctuations but stronger statistical evidence for an episodic association. These findings suggest that solar-rainfall relationships over Lagos are non-stationary and timescale-dependent, with statistically significant negative associations occurring during specific intervals despite generally weak correlations over the study period. However, the 14 significant windows are overlapping 120-month windows and should not be interpreted as 14 independent episodes. Their significance provides evidence of a temporally localised statistical association, rather than establishing a causal influence of solar activity on rainfall.

The statistically significant negative rainfall-F10.7 correlations observed around 2002–2004 suggest that enhanced solar activity was



associated with reduced rainfall anomalies over Lagos during the corresponding 120-month windows. This inverse relationship may reflect indirect solar modulation of regional atmospheric circulation, moisture

transport or West African monsoon dynamics. However, the moderate correlation magnitude and its temporal localisation suggest that any solar-related influence is neither dominant nor persistent.

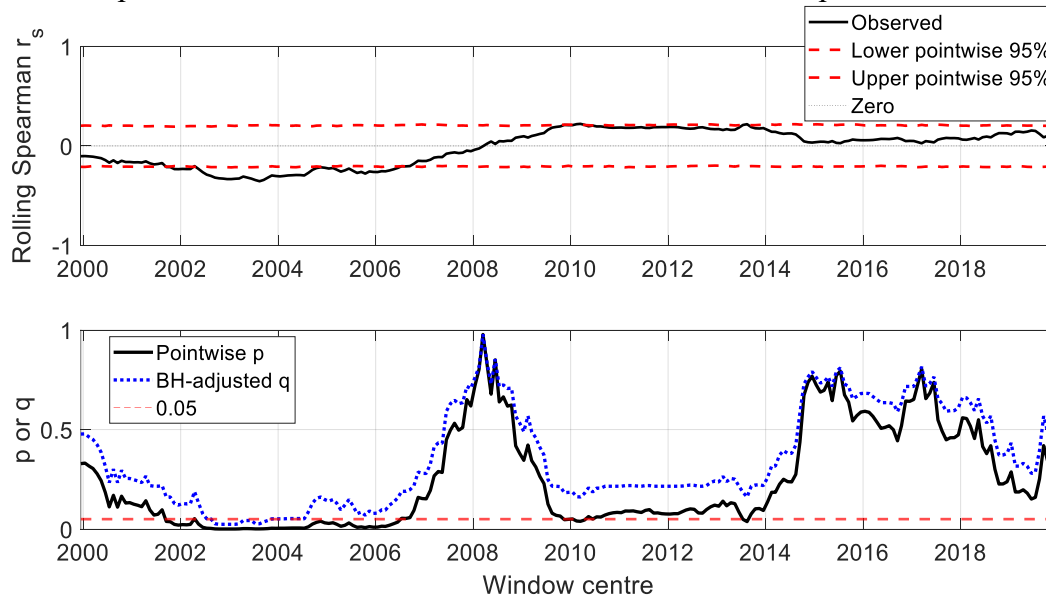


Fig. 3. The 120-month rolling Spearman correlation between monthly rainfall and F10.7 anomalies over Lagos

Further investigation incorporating tropical Atlantic sea-surface temperature, ITCZ variability and atmospheric circulation indices is required to establish whether the observed association has a physically meaningful basis. Furthermore, a 120-month rolling window centred around 2003 covers approximately 1998-2008. Thus, the significant negative correlation describes the relationship over that entire decade, not exclusively during 2003. Interestingly, this interval encompasses the maximum of Solar Cycle 23 and its subsequent declining phase. This makes it worthwhile to investigate whether the inverse rainfall-solar activity relationship reflects changing atmospheric conditions across the solar cycle.

Fig. 4 presents the 60-month rolling Spearman correlation between rainfall and geomagnetic aa-index anomalies over Lagos. The results reveal a non-stationary relationship characterised by alternating negative and positive correlations. Negative correlations peaked around 2005 ($r_s \approx -0.35$), followed by positive correlations

during 2008-2011 ($r_s \approx 0.25$), while another positive peak ($r_s \approx 0.30$) occurred around 2022. Although isolated correlations exceeded the pointwise 95% significance limits, none remained significant following Benjamini-Hochberg false discovery rate (FDR) correction ($q > 0.05$). These findings suggest that rainfall-geomagnetic associations over Lagos are temporally variable but lack robust window-specific statistical significance at the 60-month timescale. The statistically significant negative rainfall-F10.7 correlations observed around 2002-2004 suggest that enhanced solar activity was associated with reduced rainfall anomalies over Lagos during the corresponding 120-month windows. This inverse relationship may reflect indirect solar modulation of regional atmospheric circulation, moisture transport or West African monsoon dynamics. However, the moderate correlation magnitude and its temporal localisation suggest that any solar-related influence is neither dominant nor persistent.



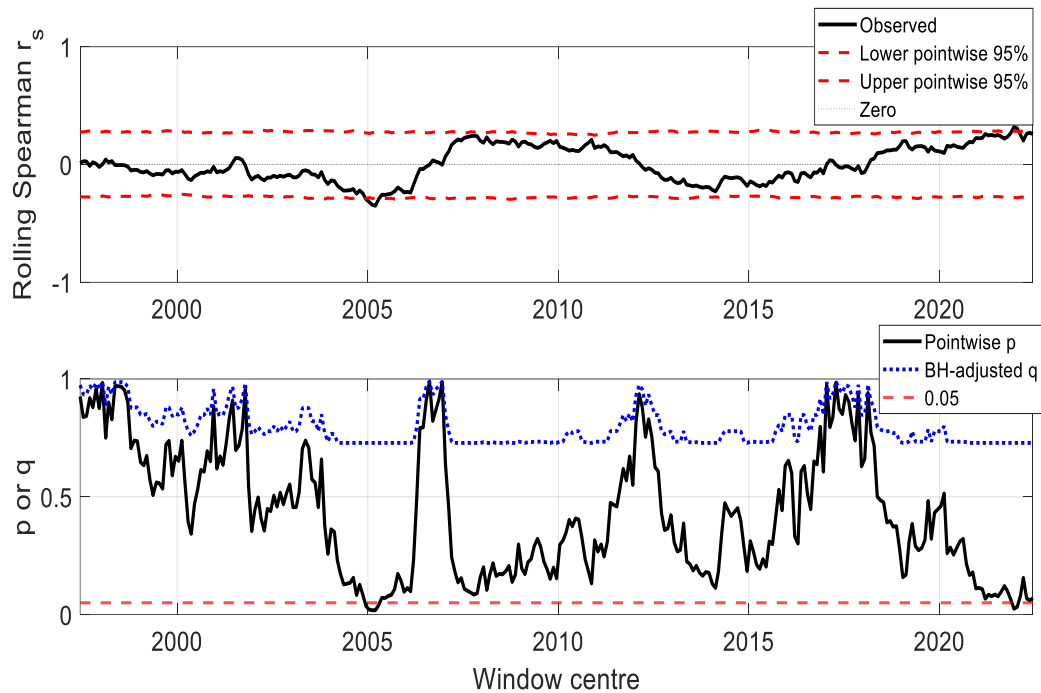


Fig. 4: 60-month rolling Spearman correlation between monthly rainfall anomalies and geomagnetic aa anomalies over Lagos, Nigeria.

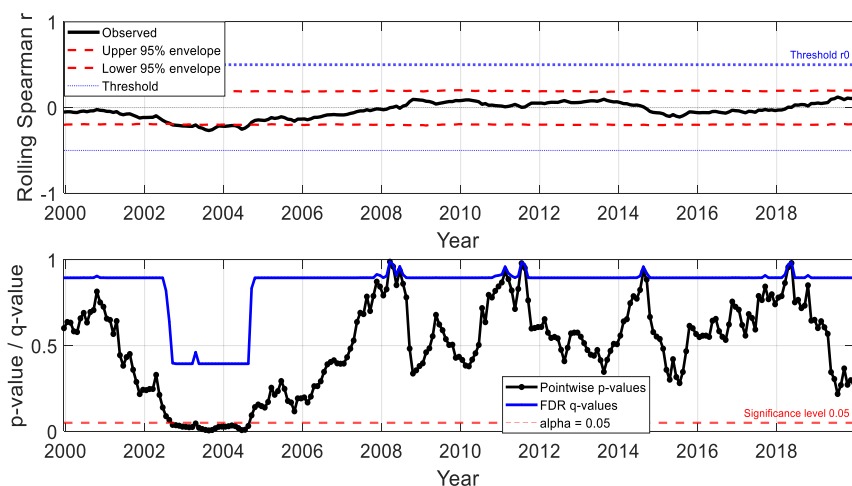


Fig. 5: The 120-month rolling Spearman correlation between monthly rainfall and geomagnetic aa anomalies over Lagos

Table 2: Summary of maximum absolute rolling Spearman correlations and statistical significance between monthly rainfall anomalies and solar–geomagnetic activity indices over Lagos

Index	Window (month)	Maximum $ r_s $	Global AR(1) p	Minimum FDR q
F10.7	60	0.482	0.0305	0.0860
F10.7	120	0.355	0.0120	0.0278
aa	60	0.350	0.3498	0.7189
aa	120	0.268	0.1039	0.3441



The statistical significances of the analyses are summarised in Table 2. It is clear that at the 5% significance level, the global rainfall-F10.7 associations are significant at both timescales, but only the 120-month analysis survives FDR correction. Neither rainfall-aa analysis achieves statistical significance.

Fig. 6 illustrates the time-frequency evolution of squared wavelet coherence between deseasonalised monthly rainfall and F10.7 solar radio flux anomalies over Lagos during 1995-2024. Colour shading represents squared wavelet coherence (-1), black contours delineate regions exceeding the

pointwise 95% significance threshold estimated from 2,000 AR(1) surrogate simulations, arrows indicate relative phase relationships, and the white dashed curve denotes the cone of influence. The results reveal intermittent, scale-dependent coherence, with three prominent regions exceeding the pointwise 95% significance threshold based on 2,000 AR(1) surrogate simulations. Significant coherence occurs at approximately 18-26-month periods during 2000-2003 and 13-17-month periods around 2008-2010.

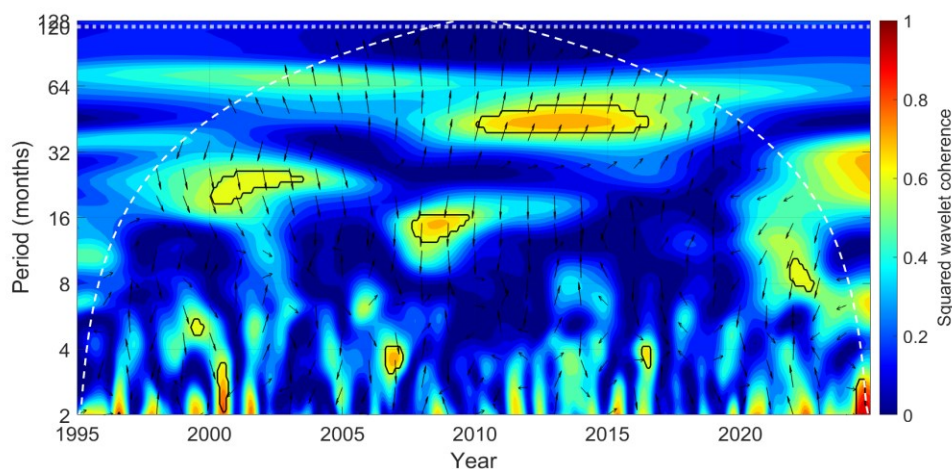


Fig. 6: Morlet wavelet coherence between deseasonalised monthly Lagos rainfall and F10.7 solar radio flux anomalies during 1995-2024.

A more persistent region extends across approximately 40-55-month periods during 2010-2016, attaining squared coherence values of about 0.7-0.8. The phase arrows exhibit varying orientations, indicating that the relative phase relationship is not uniform across timescales and epochs. These findings demonstrate that the rainfall-F10.7 association is temporally localised rather than persistent, consistent with the non-stationary behaviour identified by the rolling Spearman correlation analysis. However, the significant regions represent pointwise rather than globally corrected significance, and coherence alone does not establish causality. Fig. 7 presents the Morlet wavelet coherence between deseasonalised monthly Lagos rainfall and geomagnetic aa-index anomalies during 1995-2024. The results reveal

intermittent and scale-dependent coherence, with significant regions occurring at approximately 40-55-month periods during 2000-2003, 16-23-month periods around 2013-2015, and 13-17-month periods during 2021-2023. Additional isolated significant regions occur at shorter periods, particularly below 8 months. The most prominent coherence reaches approximately 0.6-0.8, although some regions lie close to the cone-of-influence boundary and may be affected by edge effects. Variations in phase-arrow orientation indicate non-uniform phase relationships across periods and epochs. These findings suggest episodic associations between geomagnetic activity and Lagos rainfall variability, despite the absence of globally significant rainfall-aa relationships in the rolling Spearman analysis. However,



the coherence regions satisfy pointwise 95% significance based on 2,000 AR(1) surrogate simulations and should not be interpreted as

evidence of globally significant or causal relationships.

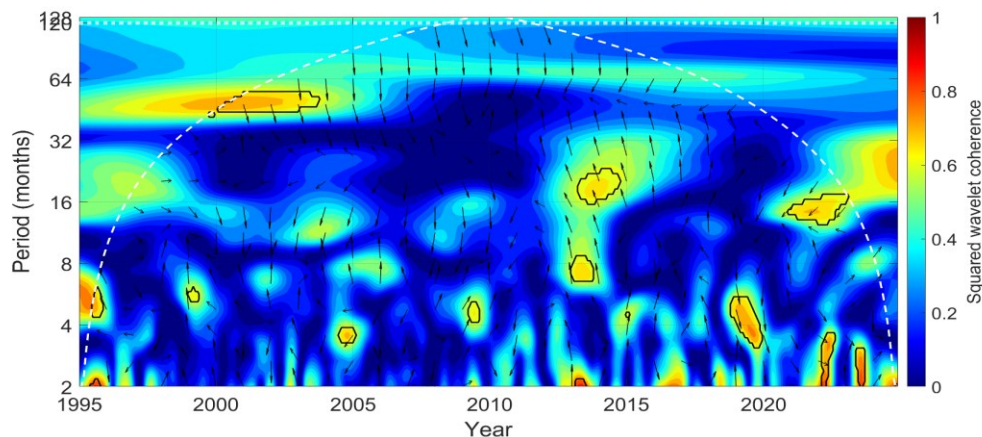


Fig. 7: Lagos Rainfall - geomagnetic aa | deseasonalised wavelet coherence Monthly anomalies; 95% pointwise AR(1) contours (N=200); COI dashed

4.0 Conclusion

This study investigated the temporal variability and statistical relationships between monthly rainfall anomalies over Lagos, Nigeria, and solar–geomagnetic activity, represented by the F10.7 solar radio flux and geomagnetic aa-index, during 1995–2024. The analysis employed 60- and 120-month rolling Spearman correlations to examine the non-stationarity of these relationships, while AR(1) surrogate-based global significance tests and false discovery rate (FDR) corrections were applied to assess their statistical robustness. Morlet wavelet coherence analysis further characterised the time–frequency dependence of the relationships, with pointwise significance evaluated using 2,000 AR(1) surrogate simulations.

The principal findings reveal a marked contrast between the rainfall-F10.7 and rainfall–aa relationships. The 60-month rainfall-F10.7 analysis exhibited alternating negative and positive correlations, with a maximum absolute correlation of 0.482 and a statistically significant global AR(1) test ($p = 0.0305$), although no individual window survived FDR correction. At the 120-month timescale, the relationship became smoother but remained statistically

significant, with a maximum absolute correlation of 0.355, global $p=0.0120$, and 14 overlapping windows surviving FDR correction. The most pronounced negative association occurred around 2002–2004, suggesting that the rainfall-solar activity relationship was particularly evident during this interval. In contrast, rainfall-aa correlations were generally weaker, with maximum absolute coefficients of 0.350 and 0.268 for the 60- and 120-month windows, respectively. Neither timescale exhibited global statistical significance ($p = 0.3498$) and ($p = 0.1039$), and no individual windows survived FDR correction.

The wavelet coherence results independently demonstrated that both relationships were intermittent and timescale-dependent. Rainfall-F10.7 coherence exhibited prominent pointwise significant regions at approximately 18–26-month periods during 2000–2003, 13–17-month periods around 2008–2010, and 40–55-month periods during 2010–2016. Rainfall-aa coherence also displayed localised significant regions, particularly at approximately 40–55-month periods during 2000–2003, 16–23-month periods around 2013–2015, and 13–17-month periods during 2021–2023. However, these wavelet significance levels were pointwise rather than globally corrected, and some



regions were affected by proximity to the cone-of-influence boundary.

Overall, the findings indicate that solar radio flux exhibits a more statistically robust, although non-stationary, association with Lagos rainfall variability than the geomagnetic aa-index over the investigated period. The results also demonstrate that relationships which appear weak when assessed over extended periods may exhibit stronger associations within particular temporal windows and frequency bands. Nevertheless, the observed statistical coherence and correlations do not establish a direct causal influence of solar or geomagnetic activity on rainfall. The study therefore highlights the importance of combining rolling correlations, appropriate multiple-testing controls, and wavelet coherence in evaluating potential solar-terrestrial climate relationships. Further investigation incorporating atmospheric circulation, oceanic variability, and physically based mechanisms would be necessary to determine whether the identified associations reflect direct or indirect solar influences on rainfall variability over southwestern Nigeria.

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5.0 References

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The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and the results presented in this paper.
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