

The Modulating Role of Tropical Atlantic Sea Surface Temperature in Solar-Rainfall Relationships over Lagos, Nigeria

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Abstract: *The influence of solar activity on tropical rainfall remains uncertain, partly because oceanic variability may modify regional climatic responses. This study investigated the modulating role of Tropical Atlantic sea surface temperature (SST) in solar-rainfall relationships over Lagos, Nigeria, during 1995-2024. Monthly rainfall, F10.7 solar radio flux and NOAA ERSSTv6 data were analysed using interaction regression involving Tropical North Atlantic (TNA), Tropical South Atlantic (TSA), Atlantic Niño (ATL3) and Atlantic Meridional Gradient (AMG) indices. Contemporaneous, 0-6-month lagged and season-specific interactions were evaluated using Newey-West heteroskedasticity- and autocorrelation-consistent inference, joint Wald tests and Benjamini-Hochberg false-discovery-rate correction. The baseline solar-rainfall relationship was insignificant ($\beta = -1.995, p = 0.516$), while no contemporaneous interaction survived statistical testing. A nominally significant TSA interaction at a two-month lead ($\beta = 11.389, p = 0.0177$) became insignificant after correction ($q = 0.496$). However, seasonal analysis identified a significant joint ATL3 interaction ($\chi^2(3) = 11.641, p = 0.0087, q = 0.0349$), with a modest explanatory contribution ($\Delta R^2 = 0.00646$). Individual seasonal differences remained insignificant. The study provides preliminary evidence of equatorial Atlantic SST-dependent solar-rainfall associations, demonstrating the importance of seasonal conditioning while highlighting limitations imposed by the relatively short observational record and limited solar-cycle coverage.*

Keywords: *Solar activity; Tropical Atlantic sea surface temperature; Rainfall variability; Atlantic Niño; Atlantic Meridional Gradient.*

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1.0 Introduction

The seasonal migration of the Intertropical Convergence Zone (ITCZ), associated with the West African monsoon system, plays a fundamental role in determining the spatial and temporal distribution of rainfall across West Africa. However, rainfall variability also exhibits substantial interannual and decadal fluctuations that cannot be explained by seasonal atmospheric circulation alone. Oceanic influences, particularly sea surface temperature (SST) anomalies in the Tropical Atlantic, have been identified as important contributors to West African rainfall variability (Giannini et al., 2003; Vizzy & Cook, 2001). Understanding how these oceanic influences interact with other potential climatic drivers is therefore essential for interpreting regional rainfall variability, particularly in coastal environments such as Lagos, Nigeria.

Solar activity has been investigated as a possible contributor to climate variability through changes in solar radiative output and associated atmospheric responses. Solar indices, including sunspot number and the 10.7 cm solar radio flux (F10.7), provide measures of solar variability over approximately 11-year activity cycles. However, the extent to which such variations influence regional rainfall remains uncertain, particularly in tropical environments where atmospheric circulation and oceanic conditions exert substantial control over precipitation. A central issue in interpreting solar-rainfall relationships is therefore the potential role of oceanic conditions in modifying the observed climatic responses. In this context, SST modulation implies that the strength, direction or temporal

characteristics of the relationship between solar activity and rainfall may depend on prevailing SST conditions (Emmanuel et al., 2024; Emmanuel et al., 2026; Emetere et al., 2015). For example, a negative solar-rainfall association under relatively warm Tropical Atlantic conditions may weaken, become statistically insignificant or reverse under cooler conditions. Such differences could reflect changes in atmospheric moisture availability, convective instability and large-scale circulation associated with contrasting SST states (Ibanga, 2025).

This concept is distinct from an indirect solar-SST-rainfall pathway, in which solar variability influences SST and subsequently affects rainfall. While SST modulation can be investigated statistically through interaction analysis and SST-conditioned relationships, establishing an indirect pathway requires additional evidence of temporal ordering, physical mechanisms and potential confounding influences.

Several Nigerian researchers have investigated relationships between solar activity and meteorological variability. Okeke and Audu (2017) examined solar and geomagnetic influences on rainfall and temperature across 15 Nigerian stations. Although their correlation analysis revealed statistically insignificant relationships between solar indices and climatic parameters, spectral analysis identified periodicities resembling known solar and geomagnetic cycles. Falaiye et al. (2021) investigated the seasonal variability of meteorological parameters in relation to solar activity at selected Nigerian stations, highlighting the importance of seasonal conditions in solar-meteorological relationships. Hanson and Okeke (2021) extended these investigations to the wet zone of West Africa during solar cycles 22–24 and found that solar and geomagnetic indices did not consistently explain regional climatic variability, suggesting the importance of other atmospheric and oceanic processes. More recently, Ibanga (2025) investigated the temporal variability of the Intertropical

Discontinuity (ITD) and its relationship with atmospheric pressure and precipitation in Lagos, Nigeria. The study distinguished strong seasonal synchronisation from weaker anomaly coupling, demonstrating that ITD migration characterises monsoon seasonality but cannot independently explain coastal rainfall variability. Collectively, these studies underscore the complexity of rainfall variability and the difficulty of establishing consistent relationships with individual climatic drivers.

Among the factors influencing rainfall variability over coastal West Africa, Tropical Atlantic SST is particularly important because SST anomalies can modify atmospheric convection, moisture transport, surface pressure gradients and the meridional displacement of the tropical rain belt (Ibanga et al., 2024).

Variability in the Tropical North Atlantic (TNA), Tropical South Atlantic (TSA) and equatorial Atlantic Niño region (ATL3), together with changes in the Atlantic Meridional Gradient (AMG), may therefore contribute to rainfall variability over Lagos. These oceanic influences provide a physical basis for investigating whether the statistical association between solar activity and rainfall changes under different Tropical Atlantic SST conditions.

Despite previous investigations of solar-rainfall relationships in Nigeria, comparatively limited attention has been given to the possibility that Tropical Atlantic SST variability modifies these relationships. Most studies have concentrated on direct correlations between solar indices and meteorological variables, while the potential conditioning role of oceanic variability has received less attention. This distinction is important because a weak overall solar-rainfall correlation does not necessarily exclude relationships that vary across SST states, rainfall seasons or preceding oceanic conditions. Nevertheless, statistical moderation should not be interpreted as evidence of a causal solar-SST-rainfall



pathway without additional supporting analysis.

Against this background, the present study investigates the modulating role of Tropical Atlantic SST in solar-rainfall relationships over Lagos, Nigeria, during 1995-2024. Monthly Lagos rainfall, F10.7 solar radio flux and NOAA Extended Reconstructed Sea Surface Temperature version 6 (ERSSTv6) data are employed to examine whether TNA, TSA, ATL3 and AMG anomalies modify the solar-rainfall association. Specifically, the study evaluates contemporaneous SST interactions, delayed influences at leads of 0-6 months and potential differences across the early rainy, late rainy and dry seasons. By incorporating seasonal controls, temporal trends, heteroskedasticity- and autocorrelation-consistent statistical inference and multiple-testing adjustments, the study seeks to distinguish statistically supported moderation from apparent associations arising from rainfall seasonality and temporal variability. The findings are expected to contribute to a better understanding of the potential conditioning role of Tropical Atlantic SST in solar-rainfall relationships over coastal West Africa.

2.0 Data and Sources

The study area (Lagos) is located in southwestern Nigeria along the Gulf of Guinea coast, approximately between latitudes 6.4°-6.7°N and longitudes 3.1°-3.6°E. Its rainfall regime is influenced by the seasonal migration of the tropical rain belt and moisture-bearing southwesterly monsoon winds from the Atlantic Ocean. Rainfall generally exhibits two maxima separated by a relative reduction during August, commonly referred to as the August break.

Monthly rainfall totals for Lagos, covering January 1995-December 2024, were obtained from the Nigerian Meteorological Agency (NiMet). The dataset comprises 360 monthly observations expressed in millimetres (mm) and constitutes the dependent variable in the statistical analyses.

Solar activity was represented by the 10.7 cm solar radio flux (F10.7), a widely used indicator of solar activity associated with the approximately 11-year solar cycle. F10.7 is measured at a frequency of 2800 MHz and expressed in solar flux units (sfu), where $1 \text{ sfu} = 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$. The F10.7 data were obtained from the Canadian solar radio flux monitoring records, with the monthly series prepared for January 1995-December 2024. The monthly observations were aligned with the Lagos rainfall record, and F10.7 was standardised before regression analysis to facilitate interpretation of its interaction with SST anomalies.

Monthly SST fields for January 1995-December 2024 were obtained from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed Sea Surface Temperature version 6 (ERSSTv6) dataset. Four indices representing major regions and thermal contrasts of the Tropical Atlantic were considered: Tropical North Atlantic (TNA), Tropical South Atlantic (TSA), Atlantic Niño (ATL3), and Atlantic Meridional Gradient (AMG). The geographical domains used to calculate the regional SST indices are summarised in Table 1.

Table 1: Geographical coordinates of the Tropical Atlantic sea surface temperature (SST)

SST index	Latitude	Longitude
TNA	5.5°–23.5°N	57.5°–15°W
TSA	20°S–0°	30°W–10°E
ATL3	3°S–3°N	20°W–0°
AMG	Derived from TNA and TSA	

3.0 Methods of Analyses

Regional mean SST values were calculated using cosine-latitude weighting. Monthly SST anomalies were subsequently obtained by subtracting the corresponding 1995–2024 calendar-month climatological means:



$$\bar{S}_r(t) = \frac{\sum_{i=1}^{n_r} S_i(t) \cos \phi_i}{\sum_{i=1}^{n_r} \cos \phi_i} \quad (1)$$

where $\bar{S}_r(t)$ represents the mean SST for region r at month t , $S_i(t)$ is the SST at grid cell i , and ϕ_i is its latitude.

Monthly SST anomalies were calculated relative to the corresponding calendar-month climatological means over 1995-2024:

$$S'_r(t) = \bar{S}_r(t) - \langle \bar{S}_r \rangle_m \quad (2)$$

where $S'_r(t)$ is the SST anomaly for region r at time t , $\bar{S}_r(t)$ is the regional mean SST at time t , and $\langle \bar{S}_r \rangle_m$ represents the long-term climatological mean SST for calendar month m , calculated over 1995-2024.

The Atlantic Meridional Gradient anomaly was defined as:

$$AMG' = TNA'(t) - TSA'(t) \quad (3)$$

where AMG' is the Atlantic Meridional Gradient anomaly at time t , $TNA'(t)$ is Tropical North Atlantic SST anomaly at time t and $TSA'(t)$ represents Tropical South Atlantic SST anomaly at time t .

These indices represent the oceanic conditions investigated as potential modulators of the F10.7-rainfall relationship over Lagos.

The baseline relationship between solar activity and Lagos rainfall was examined using multiple linear regression incorporating calendar-month controls and a linear time trend. The model was specified as:

$$R_t = \beta_0 + \beta_1 F_t + \sum_{i=2}^{12} \gamma_m D_{m,t} + \delta T_t + \varepsilon_t \quad (4)$$

where R_t represents monthly rainfall (mm), F_t is centred and standardised F10.7 solar radio flux,

$D_{m,t}$ denotes calendar-month indicator variables, T_t represents the linear time trend, and ε_t is the regression residual.

The monthly indicators account for the pronounced annual rainfall cycle, while the time trend controls for a linear change over the study period. Statistical inference was based on heteroskedasticity- and autocorrelation-consistent (HAC) standard

errors, using the Newey-West estimator with an initial bandwidth of 12 months.

To determine whether Tropical Atlantic SST variability modified the solar-rainfall relationship, separate interaction regression models were fitted for TNA', TSA', ATL3' and AMG':

$$R_t = \beta_0 + \beta_1 F_t + \beta_2 F'_t + \beta_3 (F_t S'_t) + \sum_{i=2}^{12} \gamma_m D_{m,t} + \delta T_t + \varepsilon_t \quad (5)$$

where S'_t represents the selected SST anomaly index and $F_t S'_t$ is the solar activity-SST interaction term.

The interaction coefficient β_3 measures the change in the estimated F10.7-rainfall slope associated with a 1°C increase in SST anomaly. A statistically significant interaction would indicate that the association between solar activity and rainfall depends on SST conditions.

Separate models were estimated for the four SST indices to avoid simultaneously including closely related oceanic predictors. Model performance was evaluated using the coefficient of determination (R^2) and changes in R^2 relative to the baseline model. The Benjamini-Hochberg false-discovery-rate (FDR) procedure was applied to account for multiple hypothesis testing.

Potential delayed SST influences were investigated by introducing SST anomalies preceding rainfall by 0-6 months. The lagged moderation model was expressed as:

$$R_t = \beta_0 + \beta_1 F_t + \beta_2 F'_{t-L} + \beta_3 (F_t S'_{t-L}) + \sum_{i=2}^{12} \gamma_m D_{m,t} + \delta T_t + \varepsilon_t \quad (6)$$

where L is the SST lead time in months. The analysis comprised 28 regression models, representing four SST indices at seven lead times. To ensure comparability, all lagged models were fitted using a common sample of 354 monthly observations spanning July 1995-December 2024. HAC standard errors were calculated, and FDR adjustment was applied across the 28 interaction tests.



Fig. 1. Interaction coefficients and HAC confidence intervals

The possibility that SST moderation varies with rainfall regime was examined by dividing the annual cycle into three operational seasons: the early rainy season (April–July), late rainy season (September–October), and relatively dry season (November–March). August was excluded as a transition month, leaving 330 observations. For each SST index, a pooled regression model incorporating season-specific solar activity–SST interaction terms was fitted:

$$R_t = X_t\theta + \sum_{s=1}^3 \alpha_s (F_t D_{s,t}) + \sum_{s=1}^3 \eta_s (S'_t D_{s,t}) + \sum_{s=1}^3 \lambda_s (F_t S'_t D_{s,t}) + \varepsilon_t \quad (7)$$

where X_t contains the intercept, calendar-month controls and linear trend, $D_{s,t}$ identifies rainfall regime s , and λ_s represents the season-specific F10.7-SST interaction coefficient.

Two complementary hypotheses were investigated. First, a joint Wald test examined whether all three season-specific interaction coefficients were simultaneously zero:

$$\lambda_0 = \lambda_1 = \lambda_2 = \lambda_3 = 0 \quad (8)$$

Second, pairwise contrasts examined whether the interaction coefficients differed between rainfall regimes:

$$\lambda_i - \lambda_j = 0 \quad (9)$$

The joint tests were adjusted for multiple comparisons across the four SST indices, while the 12 pairwise seasonal contrasts were evaluated using a separate FDR correction. HAC inference was calculated while preserving the original calendar-month spacing of observations.

Statistical significance was assessed at the 5% level. Given the limited number of approximately 11-year solar cycles represented within the 30-year record, statistical associations were interpreted cautiously and were not assumed to demonstrate causality.

All datasets were organised into a common monthly time series covering January 1995-

December 2024, yielding 360 complete observations. The rainfall data were expressed in millimetres, F10.7 in solar flux units and SST anomalies in degrees Celsius. The datasets were checked for temporal consistency and missing observations before analysis.

For lagged SST moderation, a common sample of 354 months (July 1995-December 2024) was retained to ensure comparability across SST lead times of 0-6 months. The seasonal analysis considered the early rainy season (April-July), late rainy season (September-October) and dry season (November-March), excluding August as a transition month and retaining 330 observations. The harmonised datasets provided the basis for evaluating contemporaneous, lagged and season-dependent SST moderation of the solar-rainfall relationship over Lagos.

4.0 Results and Discussion

Fig. 1 shows pronounced annual oscillations in TNA, TSA and ATL3 temperatures, superimposed on interannual variability. The TNA generally fluctuates between approximately 24°C and 29°C, while the TSA shows a larger seasonal range, extending from about 23°C to 28°C. ATL3 reaches temperatures exceeding 29°C in some years. It is observed that the three regions do not attain their maximum temperatures simultaneously. This reflects differences in seasonal ocean-atmosphere forcing between the Northern Hemisphere, Southern Hemisphere and equatorial Atlantic. The figure also suggests relatively warm conditions in several recent years, particularly during 2023-2024.

Fig. 2 illustrates the Tropical Atlantic SST anomalies after the mean annual cycle has been removed. TNA, TSA and ATL3 anomalies exhibit both shared and region-specific fluctuations, indicating that Tropical Atlantic SST variability is not spatially uniform. AMG anomalies alternate between positive and negative values, reflecting changes in the relative thermal conditions of



the northern and southern Tropical Atlantic. Particularly pronounced AMG departures occur around 1997, 2005, 2019-2020 and 2023, suggesting periods of substantial meridional SST contrast. These variations are

potentially relevant to the meridional position of the Atlantic ITCZ and associated West African rainfall, but the figure alone cannot establish a causal relationship.

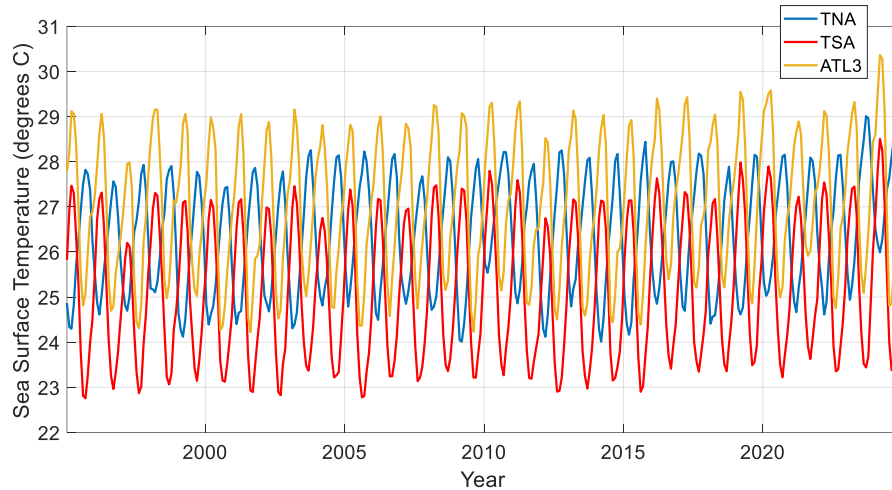


Fig. 1: Temporal variability of Tropical Atlantic SST, 1995-2024

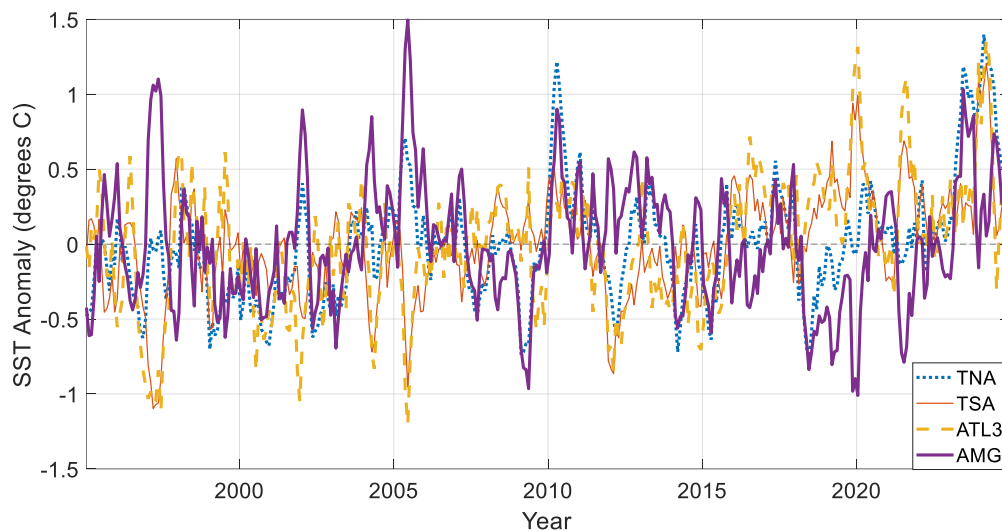


Figure 2: Tropical Atlantic SST Anomalies, 1995-2024



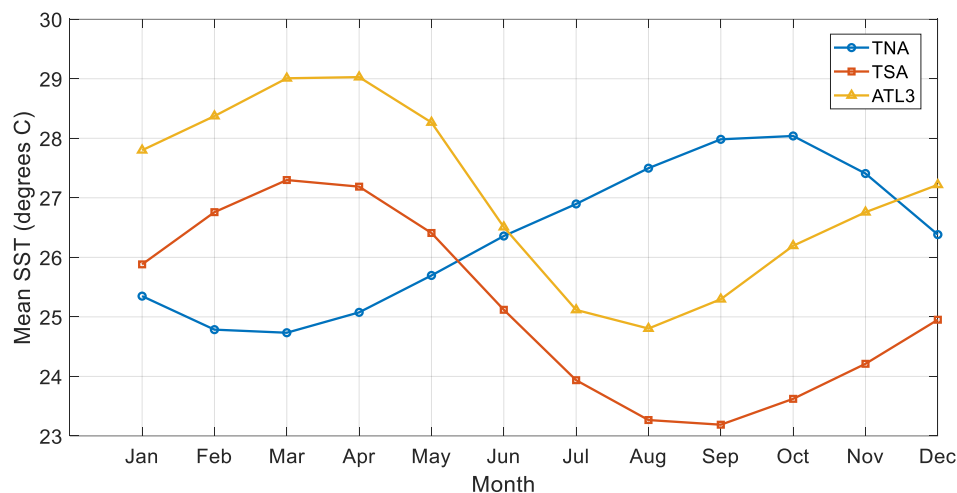


Fig. 3: Monthly Tropical Atlantic SST Climatology

The contrasting seasonal cycles produce variations in the meridional thermal structure of the Tropical Atlantic, while the SST anomaly series reveal substantial departures from the long-term monthly climatology. These characteristics provide a physical basis for investigating whether Tropical Atlantic SST anomalies and meridional gradients modulate the relationship between solar activity and rainfall over Lagos.

Fig. 4 shows that the confidence intervals for TNA, TSA, ATL3 and AMG all cross the vertical zero line. This indicates that the data do not provide sufficient evidence to reject the null hypothesis of no contemporaneous linear SST moderation. The wide confidence intervals also suggest considerable uncertainty in the estimated interaction effects.

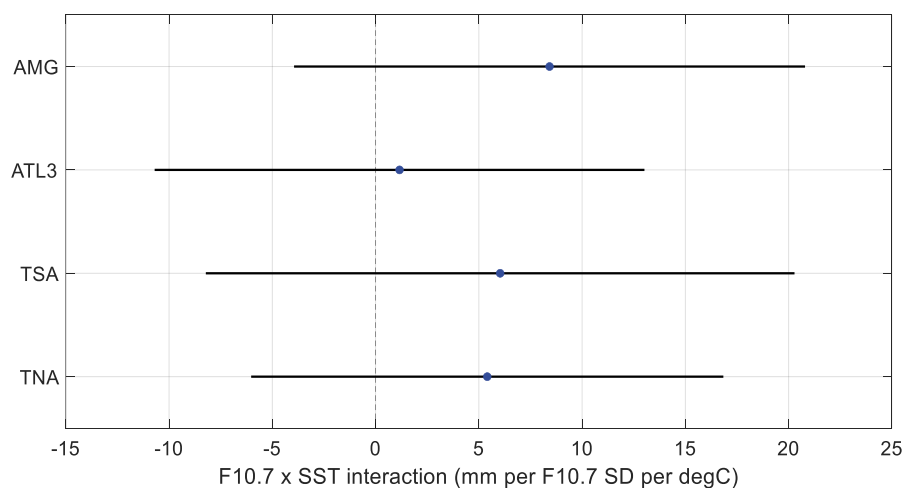


Fig. 4: Interaction coefficients and HAC confidence intervals

Fig. 5 illustrates how the estimated relationship between F10.7 and rainfall changes across SST anomaly conditions. For TNA (Fig. 5a), TSA (Fig. 5b) and AMG (Fig. 5c), the estimated slopes generally become more positive as SST anomalies increase. The ATL3 slope changes relatively little (Fig. 5d). However, the dashed confidence limits

indicate that the conditional slopes remain uncertain. Consequently, the apparent changes should be interpreted as estimated patterns rather than statistically established modulation.

It is clear that none of the four Tropical Atlantic SST indices exhibits statistically significant moderation of the F10.7-rainfall



relationship over Lagos during 1995-2024, under the contemporaneous linear interaction models tested. However, the results also suggest a direction for further investigation, particularly concerning the Atlantic Meridional Gradient (AMG). Also, the baseline model produced F10.7 regression coefficient of -1.9952 mm per F10.7 SD, HAC p-value, 0.51593, and Model R^2 of 0.6262 for the 360 observations. The negative coefficient indicates a weak estimated inverse association between F10.7 and Lagos rainfall after accounting for monthly seasonality and a linear trend. However, this association is not statistically significant ($p = 0.516$). The baseline model explains approximately 62.62% of monthly rainfall variability. Much of the explanatory power is likely attributable to the seasonal controls.

Table 2 shows that all four interaction coefficients are positive, suggesting that warmer SST anomalies or a more positive meridional SST gradient are associated with a more positive estimated F10.7-rainfall slope. Nevertheless, all HAC p-values exceed

0.05, and all 95% confidence intervals include zero. The same conclusion holds after correcting for multiple testing using the false discovery rate. The AMG interaction has the largest estimated coefficient (+8.4233) and the greatest increase in explanatory power ($\Delta R^2 = 0.0072$), but it is not statistically significant. Therefore, it cannot be concluded that AMG is a stronger moderator than the other SST indices because its estimated coefficient is larger.

The residual series (Fig. 6) exhibits pronounced positive rainfall departures and some large negative departures throughout the study period. Several substantial positive residuals occur during the later part of the record, indicating rainfall events or variability not adequately represented by the baseline model. These departures suggest that additional atmospheric and oceanic processes may influence Lagos rainfall. Residual autocorrelation and variance stability should be tested formally rather than inferred from the figure alone.

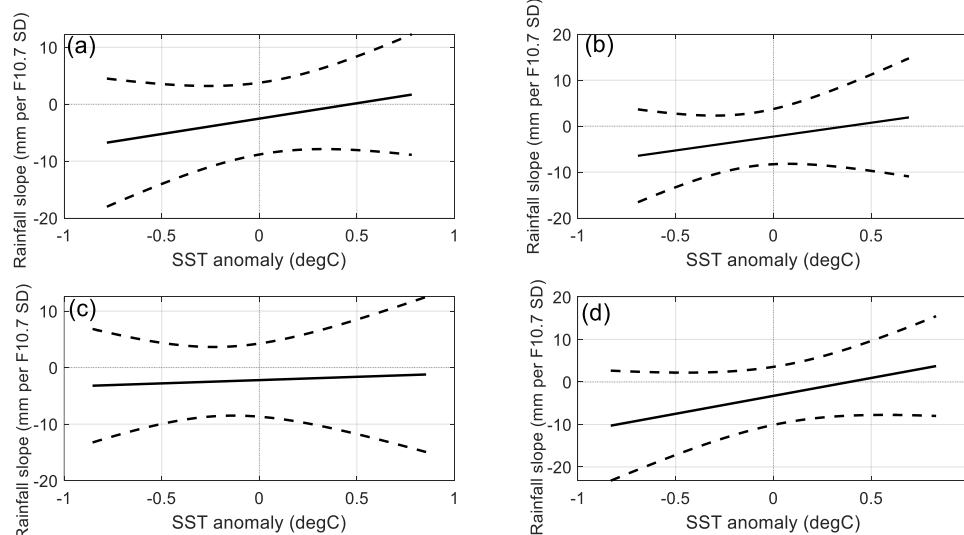


Fig. 5: Conditional F10.7-Rainfall slopes

Table 2: SST moderation results

SST index	Interaction coefficient	HAC p-value	FDR q-value	ΔR^2
TNA	+5.4073	0.3539	0.5424	0.0043
TSA	+6.0323	0.4068	0.5424	0.0017
ATL3	+1.1602	0.8479	0.8479	0.0002
AMG	+8.4233	0.1820	0.5424	0.0072



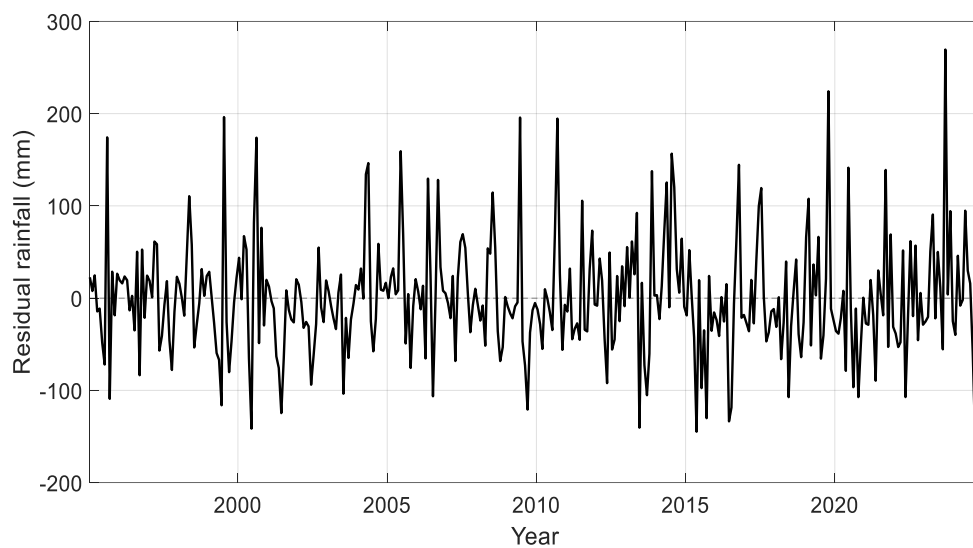


Fig. 6: Baseline Model residuals

Residual autocorrelation and variance stability should be tested formally rather than inferred from the figure alone. All four interaction coefficients are positive, suggesting that warmer SST anomalies or a more positive meridional SST gradient are associated with a more positive estimated F10.7-rainfall slope. Nevertheless, all HAC p-values exceed 0.05, and all 95% confidence intervals include zero. The same conclusion holds after correcting for multiple testing using the false discovery rate. The AMG interaction has the largest estimated coefficient (+8.4233) and the greatest increase in explanatory power ($\Delta R^2 = 0.0072$), but it is not statistically significant. Therefore, we cannot conclude that AMG is a stronger moderator than the other SST indices.

Lagged interaction regression was employed to investigate whether Tropical Atlantic SST anomalies preceding rainfall by 0-6 months modified the relationship between F10.7 solar radio flux and monthly rainfall over Lagos during 1995-2024. The analysis comprised 28 models representing four SST indices and seven lead times, using a common sample of 354 monthly observations. The baseline regression indicated a weak and statistically insignificant association between F10.7 and rainfall ($\beta = -2.0644$ mm per standard

deviation of F10.7; HAC $p = 0.496$), with an explanatory power of $R^2 = 0.6240$. The first heatmap (Fig. 7a) shows considerable variation in estimated interaction coefficients across SST indices and lead times. The largest positive coefficient occurs for TSA at a two-month lead ($\beta = +11.389$), followed by AMG at a one-month lead ($\beta = +8.392$). The largest negative estimate occurs for TNA at a six-month lead ($\beta = -4.276$). The second heatmap (Fig. 7b) provides the most decisive statistical evidence.

The TSA interaction at a two-month lead has an unadjusted HAC p-value of 0.0177, below the conventional 0.05 threshold. However, its FDR-adjusted q-value is 0.496, indicating that the result does not survive correction for the 28 comparisons. Consequently, the TSA result should be described as exploratory or nominally significant, not as confirmed evidence of SST moderation.

These variations suggest possible differences in the estimated solar-rainfall relationship under different SST conditions. Nevertheless, coefficient magnitude alone cannot establish statistical significance.

Fig. 8 presents the interaction coefficients and their 95% HAC confidence intervals for F10.7 and SST anomalies at leads of 0-6 months: (a) TNA, (b) TSA, (c) ATL3 and (d) AMG. The coefficients varied across SST indices and lead times, with the largest



positive estimates occurring for TSA at a two-month lead ($\beta = 11.389$) and AMG at a one-month lead ($\beta = 8.392$). The TSA two-month interaction was nominally significant ($p = 0.0177$), with its confidence interval excluding zero. However, it did not remain significant after false-discovery-rate correction ($q = 0.496$). All other confidence intervals included zero, and none of the 28 interactions survived multiple-testing correction.

These findings indicate that Tropical Atlantic SST anomalies at leads of up to six months

do not provide statistically robust evidence of linear modulation of the solar-rainfall relationship over Lagos. Although the two-month TSA interaction suggests a possible delayed association, its lack of multiplicity-adjusted significance and small incremental explanatory contribution warrant cautious interpretation. The results therefore motivate further investigation of seasonal dependence and timescale-specific relationships, rather than supporting a definitive SST-mediated solar influence on Lagos rainfall.

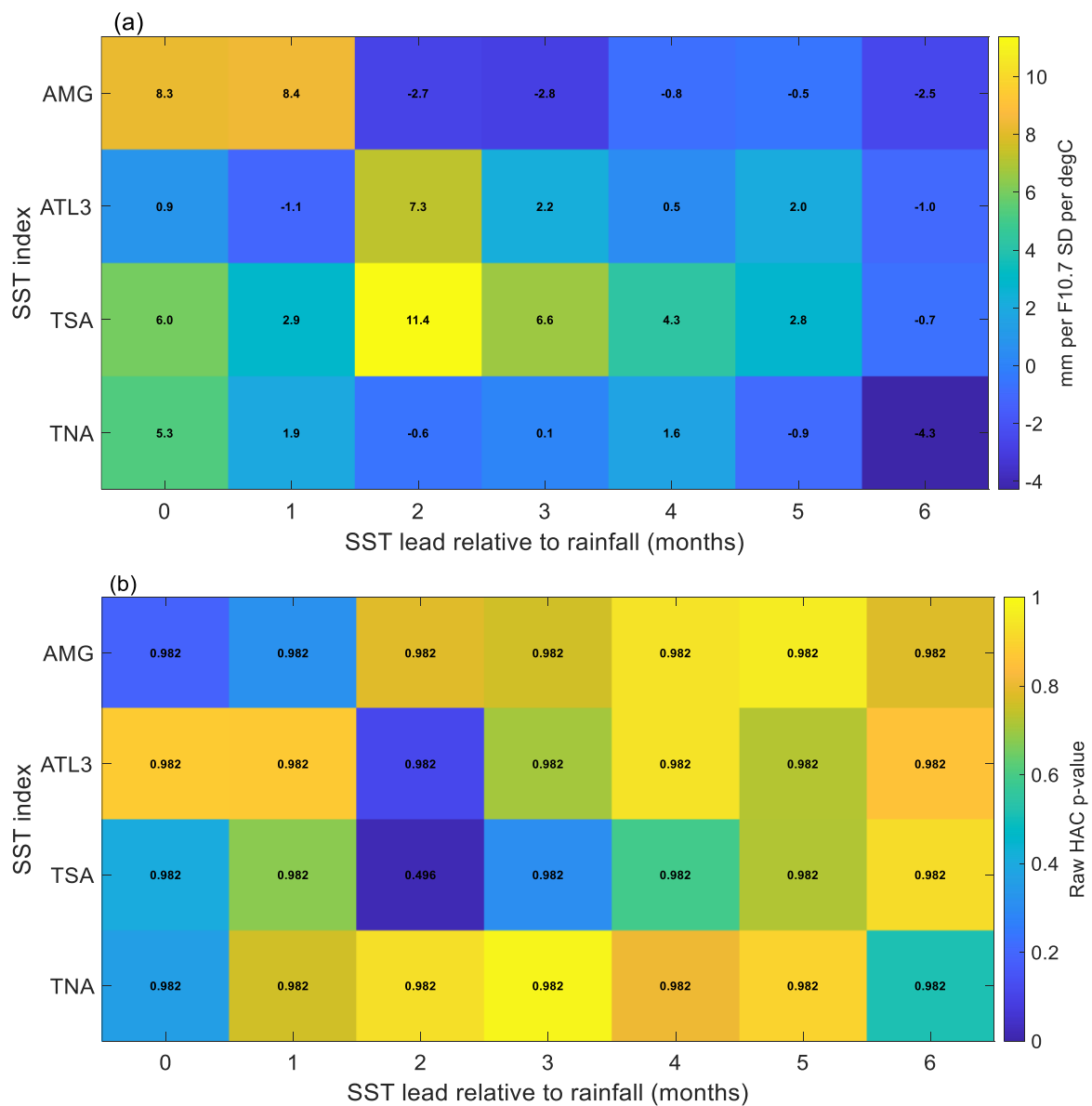


Fig. 7: (a) Lagged interaction coefficient heatmap (b) HAC p-values and FDR-adjusted significance



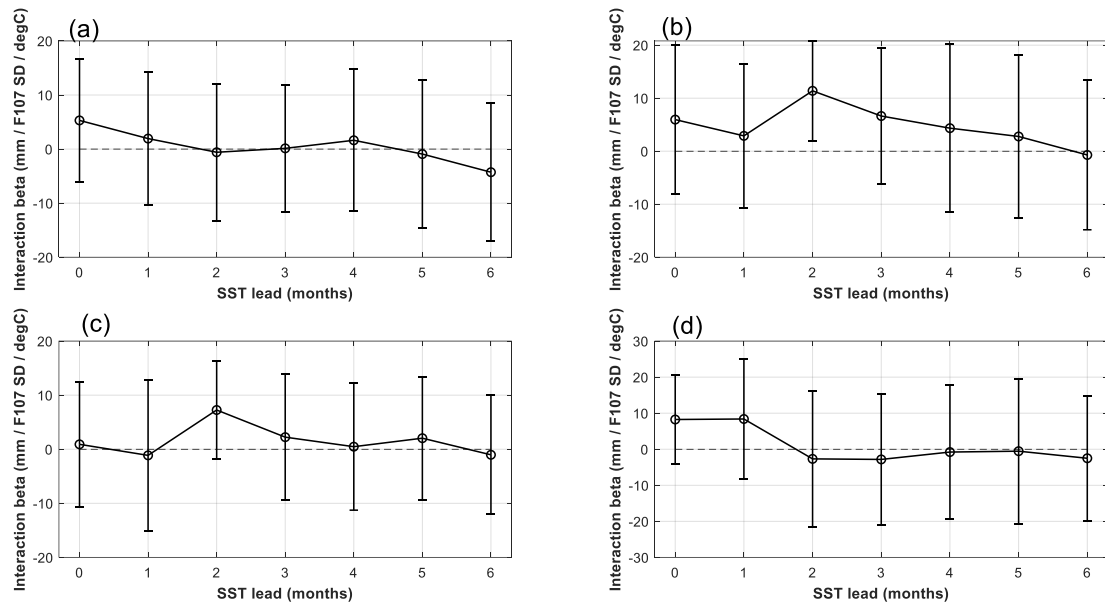


Fig. 8: Interaction coefficients and confidence intervals

The seasonal moderation analysis examined the F10.7-SST interactions during the early rainy season (April-July), late rainy season (September-October) and dry season (November-March), using 330 monthly observations from 1995-2024. Fig. 9 shows that the interaction coefficients varied across SST indices and rainfall seasons. TNA, TSA and ATL3 exhibited positive coefficients during the early rainy season, negative coefficients during the late rainy season and positive coefficients during the dry season. However, none of the 12 individual interactions remained significant after false-discovery-rate (FDR) correction, as indicated by the q -values in Fig. 9.

Fig. 10 illustrates the interaction coefficients and their 95% heteroskedasticity- and autocorrelation-consistent (HAC) confidence intervals. The relatively wide confidence intervals, particularly during the late rainy season, indicate substantial uncertainty in the estimated interactions. This uncertainty may partly reflect the smaller number of observations available for September-October ($n = 60$). Among the individual coefficients, the ATL3 dry-season interaction was nominally significant ($\beta = 7.961$, $p = 0.0203$; 95% CI: 1.237-14.686), indicating that the estimated F10.7-rainfall slope became more positive with increasing ATL3

SST anomalies during November-March. However, none of the 12 individual season-specific interactions remained significant following Benjamini-Hochberg false-discovery-rate (FDR) correction.

Only ATL3 exhibits a significant joint interaction. Fig. 11 presents the interaction coefficients with their 95% HAC confidence intervals. The wide intervals, particularly during the late rainy season, indicate considerable uncertainty in the estimates. The ATL3 dry-season interaction was nominally significant ($\beta = 7.961$, $p = 0.0203$), but did not survive FDR correction ($q = 0.244$). The joint Wald tests (Figure 9) identified ATL3 as the only SST index exhibiting a statistically significant joint interaction ($\chi^2(3) = 11.641$, $p = 0.0087$, $q = 0.0349$).

The corresponding tests for TNA, TSA and AMG were not significant. Nevertheless, the ATL3 interaction terms increased the proportion of explained rainfall variance by only 0.65 percentage points ($\Delta R^2 = 0.00646$). Furthermore, none of the pairwise differences between seasonal interaction coefficients remained significant after FDR correction. Unlike the contemporaneous and lagged analyses, which revealed no statistically robust moderation, the seasonal analysis provides preliminary evidence of an ATL3-dependent solar-rainfall association.



However, the significant joint test does not establish differences in moderation between rainfall seasons. The modest explanatory

contribution, uncertainty in the estimates and limited number of solar cycles covered by the study warrant cautious interpretation.

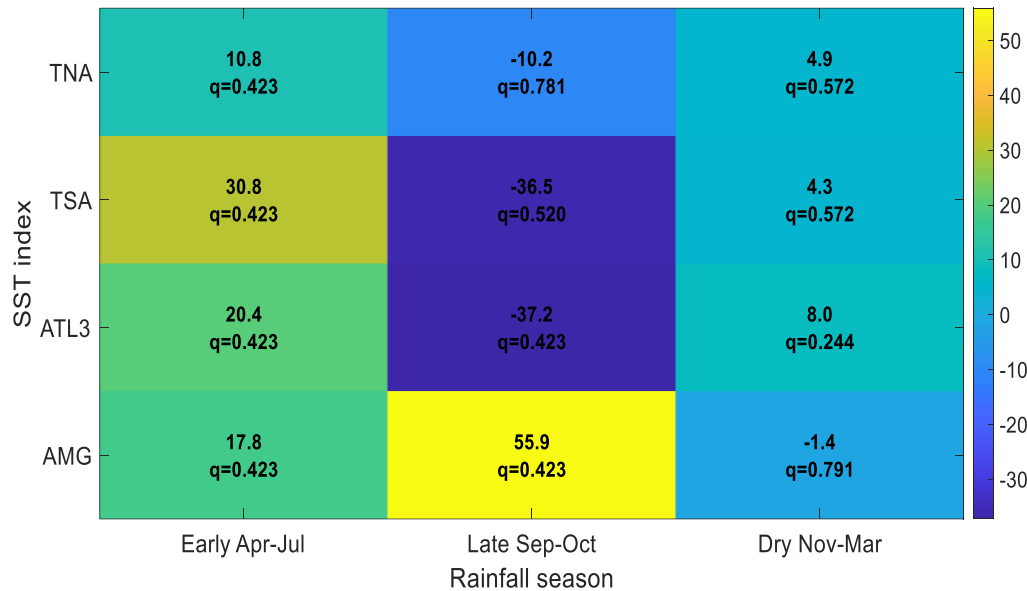


Fig. 9. Season-specific interaction coefficients between F10.7 solar radio flux and Tropical Atlantic SST anomalies (TNA, TSA, ATL3 and AMG) over Lagos during 1995-2024.

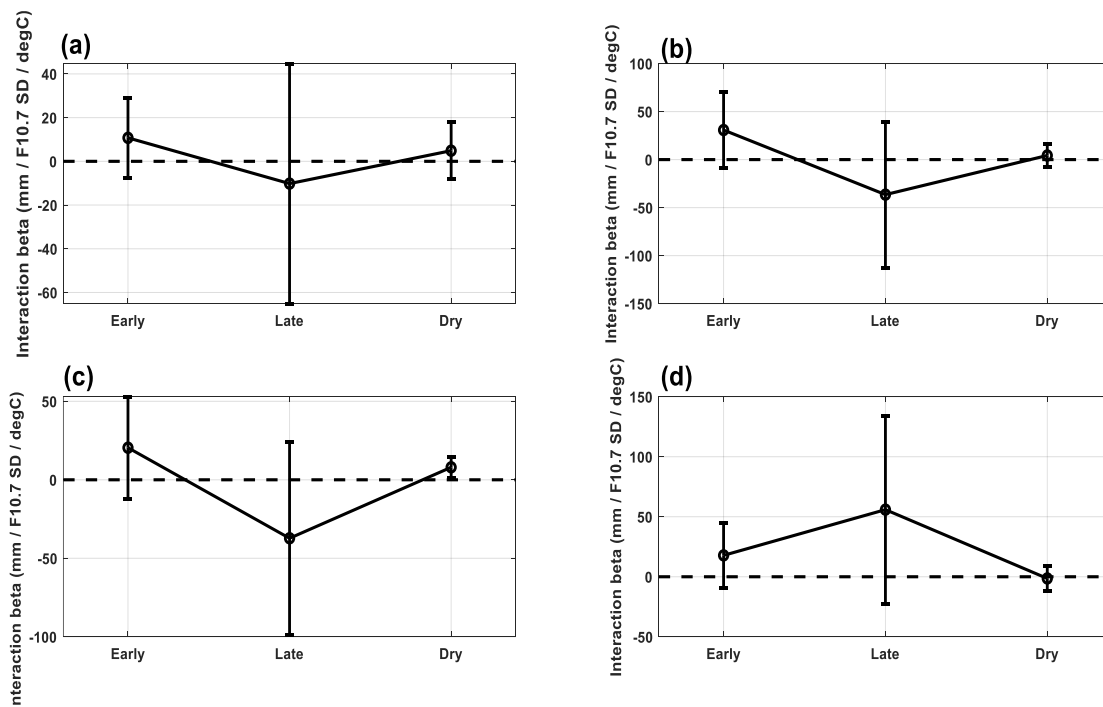


Fig. 10: Season-specific F10.7-SST interaction coefficients and corresponding 95% HAC confidence intervals for (a) TNA, (b) TSA, (c) ATL3 and (d) AMG. Dashed horizontal lines indicate zero interaction



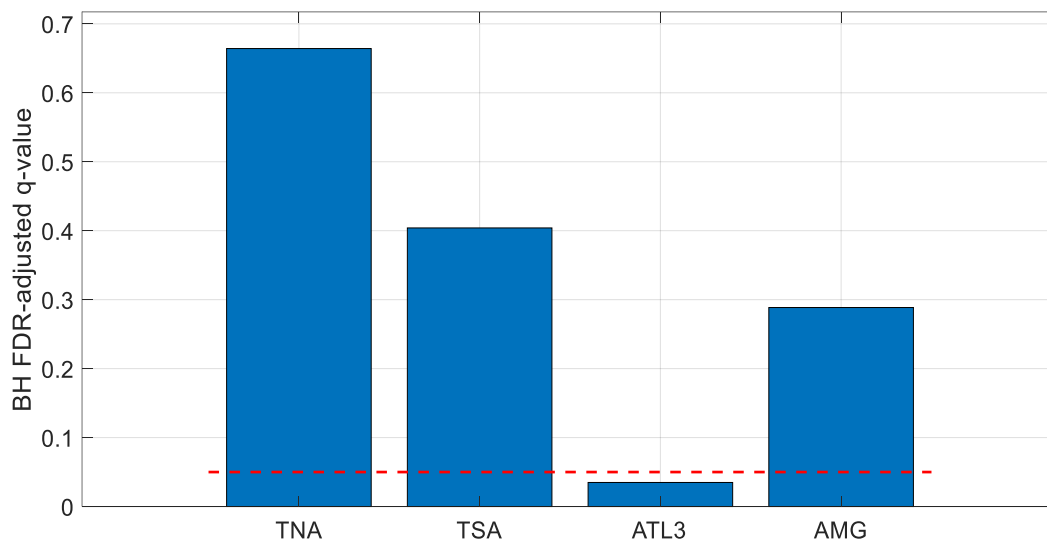


Fig. 11. FDR-adjusted q-values from joint Wald tests of season-specific F10.7-SST interactions for the four Tropical Atlantic SST indices. The red dashed line indicates the 5% significance threshold.

5.0 Conclusion

This study investigated the modulating role of Tropical Atlantic sea surface temperature (SST) in the relationship between F10.7 solar radio flux and rainfall over Lagos, Nigeria, during 1995–2024. Using 360 monthly observations, the analysis examined contemporaneous, lagged and season-dependent interactions involving TNA, TSA, ATL3 and AMG SST anomalies.

The baseline analysis revealed no significant direct F10.7–rainfall relationship. $\beta = -1.995, p = 0.516$). Similarly, none of the contemporaneous SST interactions was statistically significant after false-discovery-rate (FDR) correction. The lagged analysis identified a nominally significant TSA interaction at a two-month lead ($\beta = 11.389, p = 0.0177$), but this did not survive FDR correction ($q = 0.496$). However, the seasonal analysis identified a significant joint ATL3 interaction ($\chi^2(3) = 11.641, p = 0.0087, q = 0.0349$), although its additional contribution to explained rainfall variance was modest ($\Delta R^2 = 0.00646$). Neither the individual seasonal interactions nor their pairwise differences remained significant after multiple-testing correction.

Overall, the findings provide preliminary statistical evidence that equatorial Atlantic SST variability may condition the solar–rainfall relationship over Lagos, particularly within a seasonally structured framework. However, the limited explanatory contribution and the relatively small number of solar cycles represented in the 30-year record constrain the strength of this inference. Longer observational records and additional atmospheric and oceanic controls are therefore recommended to establish the robustness and physical significance of the observed ATL3 interaction.

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for the F10.7 cm solar radio flux observations.

6.0 References

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Declarations

Consent for publication

Not Applicable

Data Availability Statement:

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflict of Interest

The authors have no competing interests to declare that are relevant to the content of this article.

Ethical Considerations

Not applicable

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Authors' Contributions

All components of the work were carried out by the author

