npj | climate and atmospheric science

Article

Published in partnership with CECCR at King Abdulaziz University

https://doi.org/10.1038/s41612-026-01325-8

Breaking the link: warming disrupts early-season rainfall predictability in the Caribbean

Leonardo A. Clarke[1], Jhordanne J. Jones[1] ✉, Michael A. Taylor[1], Matthew St. Michael Williams[1], Tajay Edwards[2] & Tannecia S. Stephenson[1]

Sea surface temperatures (SSTs) in the tropical North Atlantic have historically served as reliable predictors of early-season rainfall across the Caribbean. In particular, rainfall onset has been linked to SSTs exceeding the convective threshold necessary to support deep convection. However, recent warming trends appear to have altered this relationship. Here, we show that although SSTs routinely exceed the convective threshold earlier in the season, early rainfall has not increased. This decoupling reflects a shift in the atmospheric state, with enhanced stability, evidenced by reduced convective available potential energy and increased convective inhibition, increasingly suppressing convection. Reduced rainfall results in a more persistent Caribbean Low-Level Jet (CLLJ), further inhibiting rainfall by promoting subsidence and dry air advection. Correlations indicate that dynamic atmospheric variables now explain a larger share of rainfall variability than absolute SSTs. These findings signal a regime shift in Caribbean rainfall dynamics and raise concerns about the declining utility of SST-based predictors under continued climate warming. These results have significant implications for seasonal forecasting and adaptation planning across Caribbean Small Island Developing States.

Seasonal rainfall in the Caribbean plays a vital role in agriculture, water resource management, and socioeconomic stability. Historically, sea surface temperatures (SSTs) have been reliable predictors of rainfall variability across the region. However, ongoing climate change necessitates a reassessment of this relationship. Global warming is altering traditional seasonal indicators, such as SST, undermining the reliability of early warning systems that depend on them and complicating planning across multiple sectors, including water resources and disaster preparedness[1,2]. The unprecedented early formation of Category 4 Hurricane Beryl in June 2024 underscores the urgent need for Caribbean nations to adapt to an increasingly unpredictable climate regime. Therefore, understanding how global climate change is reshaping Caribbean rainfall climatology is critical for enhancing regional preparedness, adaptation, and resilience.

Caribbean rainfall climatology exhibits a distinct bimodal pattern, with two prominent peaks: the early rainfall season from May to July (MJJ) and the late rainfall season from September to November[3–5]. These are separated by a relatively dry period during July-August, commonly known as the mid-summer drought (MSD). The MSD is particularly pronounced in the northwestern Caribbean and coincides with the summer peak of the Caribbean Low-Level Jet (CLLJ), defined as enhanced low-level easterly wind flow at 925-hPa exceeding $14\,m\,s^{-1}$ across the central Caribbean[6–8]. Notably, the mechanisms governing rainfall onset differ between the two seasons[4,9].

Early-season rainfall has historically been strongly linked to SSTs in the tropical North Atlantic (tNA). The seasonal onset of convection-inducing SSTs greater than 27 °C is the result of the eastward progression of the Atlantic Warm Pool (AWP, defined as SSTs ≥28.5 °C) from the Gulf of Mexico and western Caribbean into the broader Atlantic (Fig. S1). A warmer environment increases low- to mid-level relative humidity[10,11]. This increased moisture drives greater atmospheric instability, facilitates an increase in northward flow over the Caribbean region that weakens the low-level easterly flow and westward reach of the North Atlantic subtropical high (NASH). With a weaker CLLJ, low-level southerly winds dominate the mean flow and advect additional moisture into the Caribbean Basin from the northward-displaced Pacific Intertropical Convergence Zone (ITCZ)[11,12]. All of these factors promote large-scale convergence and atmospheric instability, which trigger rainfall during the early season.

In contrast, during the late season, the AWP extent is at its maximum, and SSTs across the Caribbean and the tNA exceed the convective range (27 °C–29 °C). Generally, late-season SSTs may fall beyond the convective range and reach as high as 30 °C. At this range, the SST-rainfall relationship weakens as SSTs homogenize across the region. With little sensitivity to

[1]Department of Physics, University of the West Indies, Kingston, Jamaica. [2]Caribbean Institute for Meteorology and Hydrology, Bridgetown, Barbados.
✉e-mail: jhordanne.jones@uwi.edu

SSTs, late-season convection is mostly driven by the large-scale atmospheric circulation and regions of ascent and descent[13,14]. Additionally, regional ITCZs begin to shift southward, suppressing convergence and stifling the supply of moisture to the Caribbean region. Consequently, the CLLJ begins to strengthen, ending the late-season rainfall[7,11,12,15]. With late-season SSTs exceeding 29 °C, other factors driven predominantly by interannual and multidecadal variability, such as vertical wind shear or relative SSTs (i.e., the deviation of local SSTs from the tropical mean), play a more decisive role in rainfall variability[15]. The role of El Niño Southern Oscillation (ENSO) in driving vertical wind shear within the Caribbean and wider tNA has been well researched[4,15–20]. El Niño conditions strengthen vertical wind shear across the region and suppress rainfall; La Niña conditions weaken vertical wind shear and promote low-level convergence and convection. Notably, relative SST is a robust predictor of tropical atmospheric stability and rainfall variability[21–23].

As SSTs across the Caribbean and tNA continue to rise due to global warming, with regions of the Caribbean exceeding the convective range earlier in the year, emerging evidence suggests that long-held assumptions about the drivers of early-season Caribbean rainfall may be shifting. This shift could render current prediction frameworks that rely on static SST thresholds unreliable. The implications for Caribbean Small Island Developing States (SIDS) are significant, affecting their capacity to anticipate rainfall variability and respond effectively to climate extremes.

In this paper, we highlight this emerging concern by examining recent trends in the SST convective threshold in the tNA region and evaluating their implications for the timing and mechanisms of early-season rainfall onset. We show that with global warming, Caribbean early rainfall season SSTs exceed the convective range earlier in the year, contributing to the weakening of the traditional SST-rainfall relationship. We further suggest that relative SSTs and, consequently, the CLLJ may become more reliable indicators of rainfall onset in the region. Our aim is to encourage further investigation into this critical transition. "Results" outlines the study domain, datasets, and methods. "Discussion" presents the results of the analysis, and "Methods" offers a summary and concluding discussion.

Results

Is the SST-rainfall relationship breaking down for the early rainfall season?

The evolving relationship between Caribbean sea surface temperatures (SST_{CAR}) and precipitation is illustrated in Fig. 1a. The top panel illustrates the monthly Caribbean rainfall rates versus the absolute SSTs from 1979 to 2024. During the dry season (indicated by the gray oval), both SST and rainfall were relatively low. In contrast, the early rainfall season (May-July; green oval) displayed a robust linear relationship, with higher SSTs in this regime associated with greater rainfall. This is consistent with the notion that early season rainfall is sensitive to SSTs surpassing the convective threshold required for sustained atmospheric instability[11,14]. Variability in ocean surface temperatures around this threshold, for example, due to changes in the eastern extent of the Atlantic Warm Pool, modulates the intensity of African easterly waves and other forms of convective activity within the Caribbean[24–26], beginning in May and June. However, the late rainfall season (September-November) behaves differently. In the presence

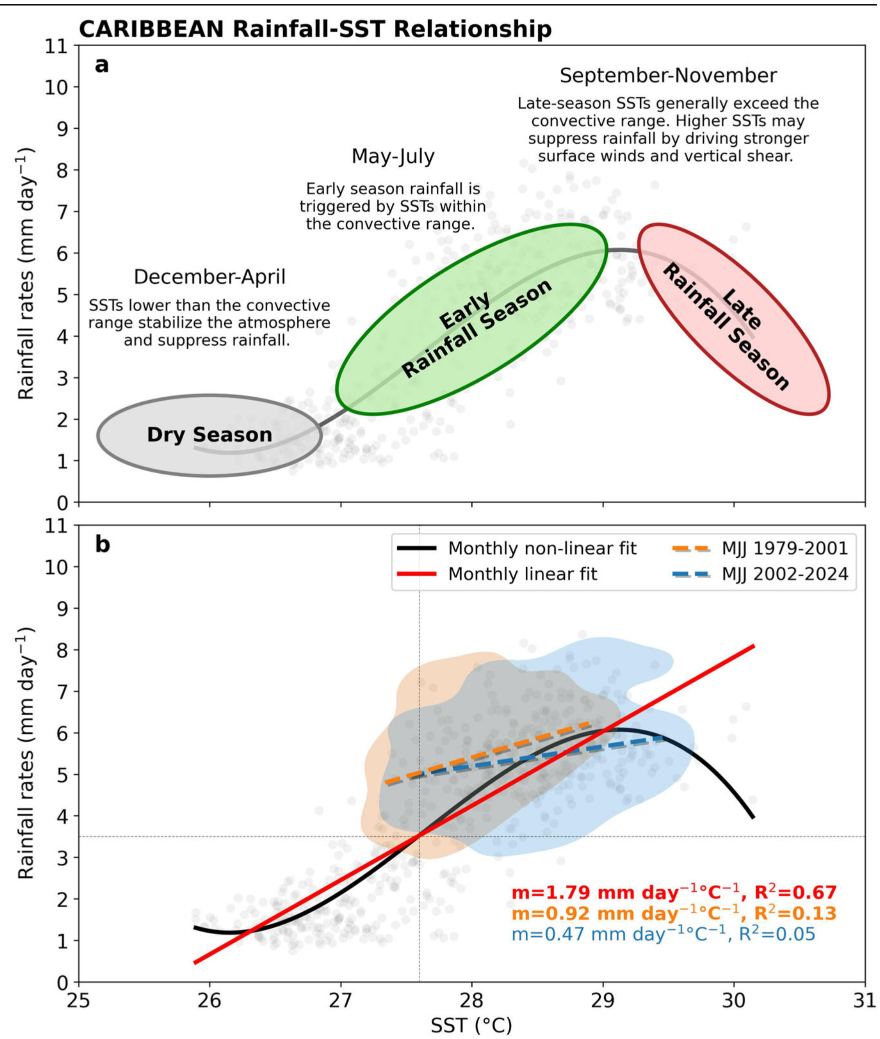

Fig. 1 | The Caribbean rainfall-SST relationship from 1979–2024. a Schematic of the rainfall-SST relationship and an approximate categorization of the relationship for the wet (early and late seasons) and dry seasons for the Caribbean region. Monthly observations between 1979 and 2024 are shown in the gray scatterplot. The solid black line indicates the nonlinear fit. **b** The kernel density estimation (KDE) distributions of monthly data for Caribbean early season (May–July) rainfall for 22-year time periods 1979–2001 and 2002–2024, are shaded in orange and blue, respectively. As in the top panel, the black solid line indicates the same nonlinear fit of the monthly data, and the red solid line indicates the linear fit. Thick dashed lines illustrate the rainfall-SST linear relationship for each climate norm. The slope of each line is given in the bottom right corner; the bold font indicates statistical significance at the 95% confidence level. Thin dotted lines indicate the static convective threshold defined as 27.6 °C in SST and 3.5 mm day^{-1} in rainfall.

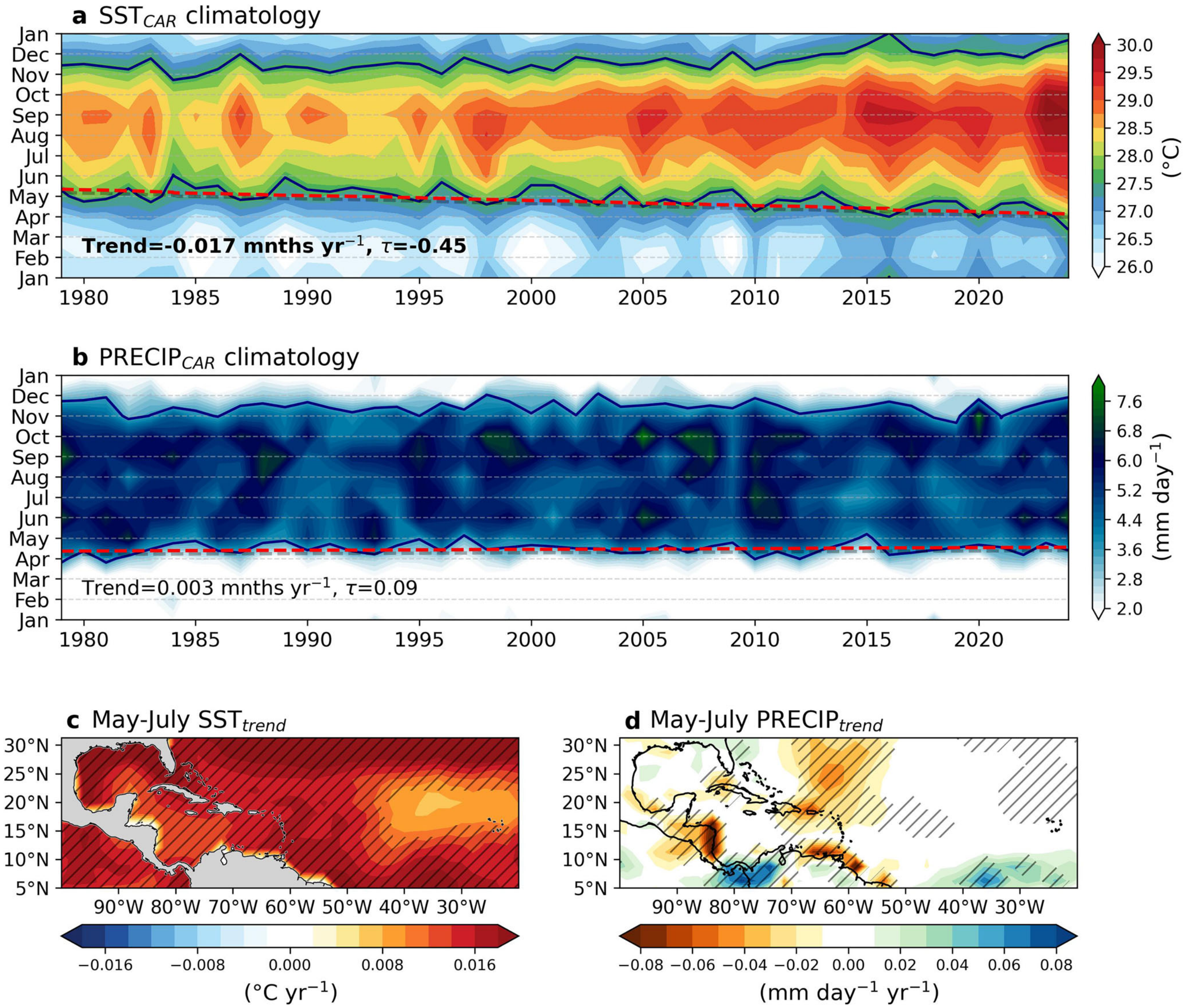

Fig. 2 | Trends in early-season Caribbean SST and precipitation. The evolution of the sea surface temperature (**a**, SST$_{CAR}$) and precipitation rate (**b**, PRECIP$_{CAR}$) monthly climatologies averaged over 1979–2024. The dark blue contours in the top panel highlight the 27.6 °C contour, indicating the general lower limit of the convective range[14,28,29], while the 3.5 mm day^{-1} contour is highlighted in the middle panel. The red dashed lines indicate the linear trend of the onset of each threshold. The linear trend and non-parametric Kendall-τ value are given in the lower left corner and highlighted in bold to indicate statistical significance at the 95% confidence level. A positive trend indicates a later onset, whereas a negative trend indicates an earlier onset. The Kendall-τ value indicates the strength of the monotonic trend. **c**, **d** The linear trend in May-July SSTs and PRECIP at each grid point, with hatched regions indicating statistical significance at the 95% confidence level. Monthly SST and PRECIP data were sourced from ERSSTv5 and NOAA's GPCP, respectively.

of uniformly high SSTs, the SST-rainfall relationship weakens, and in some instances, the warmest SSTs are associated with rainfall suppression[25]. This decoupling reflects the diminished influence of absolute SSTs in the late season and the modulation of convection by other factors such as wind shear.

Figure 1b illustrates the SST-rainfall relationship during the dry, early-rainfall, and late-rainfall seasons. In general, the linear relationship between Caribbean SSTs and rainfall is strong, with a slope of 1.8 mm day^{-1} °C^{-1}. The figure also highlights the difference in the strength of the SST-rainfall relationship between two consecutive 23-year periods: 1979–2001 and 2002-2024. The more recent 2002–2024 time period shows a slightly weaker SST-rainfall association (0.47 mm day^{-1} °C^{-1}) than the earlier 1979–2001 time period (0.92 mm day^{-1} °C^{-1}). The later period also noticeably shifted to warmer SSTs and had increased variance relative to the earlier period. The latter period is characterized by a warm phase of the Atlantic Multidecadal Oscillation (AMO) and stronger anthropogenic warming (see Fig. 2). Recent findings by Hibbert et al.[20] and He et al.[27] indicate that the AMO is not the dominant contributor to the observed warming of Atlantic SSTs in recent decades; rather, there is an increasing influence of externally forced climate change on regional ocean-atmosphere interactions.

The results suggest that when early-season SSTs in the tNA and Caribbean are predisposed to exceeding the convective range (27°-29°C), the linear relationship between absolute SSTs and rainfall is weaker, as in the earlier climatological period. However, recent warming associated with global warming (Figure 2) may fundamentally alter the SST-rainfall relationship in the early season by ushering in an era of persistent exceedance of the convective threshold, similar to the late season. The conventional understanding is that the predictive power of absolute SSTs is largely contingent on the environmental proximity to this threshold. If the tNA remains persistently above this convective baseline, the utility of SST magnitude as a predictor of early season rainfall in the climate change era will be eroded. Such a regime shift would mark a profound change in the hydroclimate of the region.

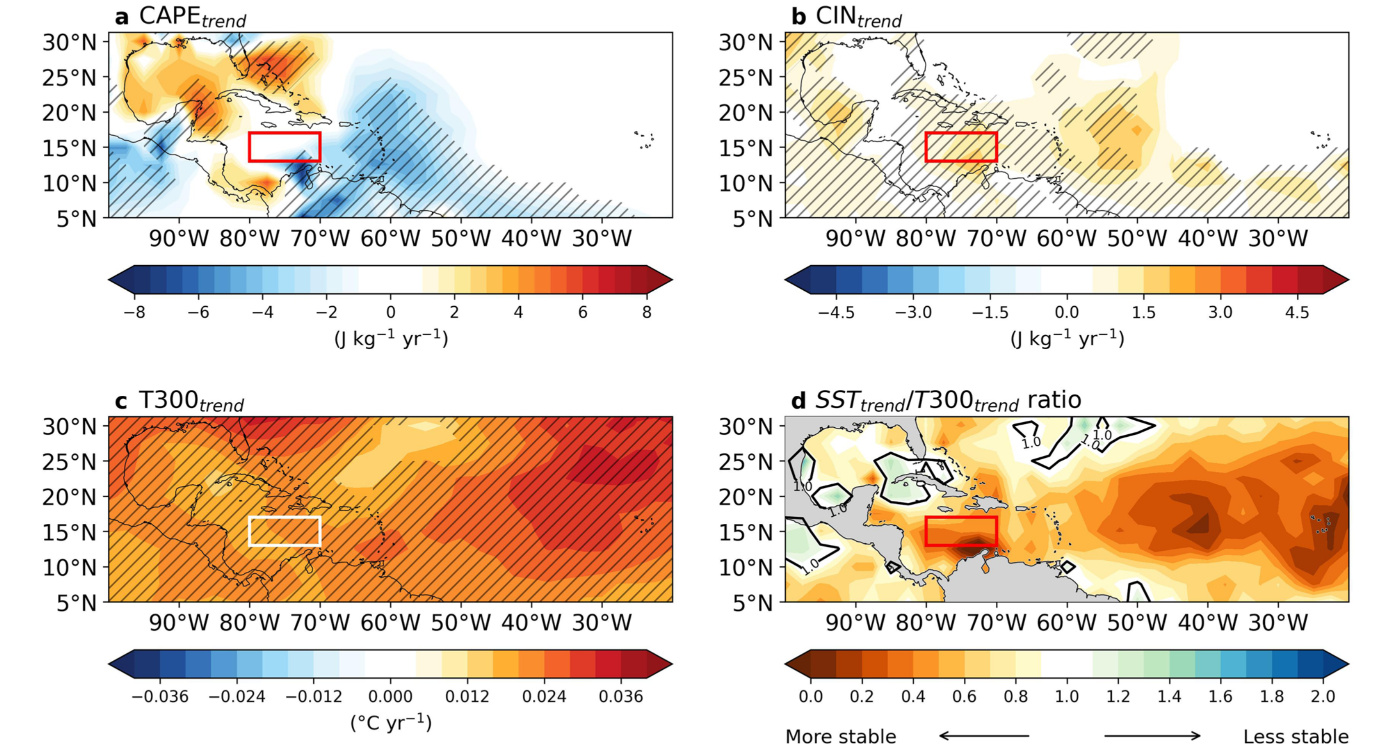

Fig. 3 | Spatial trends in May-July thermodynamic variables across the Caribbean. Trends in the May–July **a** convective available potential energy (CAPE), **b** convective inhibition (CIN), **c** 300-hPa air temperatures (T300), and **d** the ratio between SST_{trend} and $T300_{trend}$ from 1979 to 2024. Hatches indicate statistical significance at the 95% confidence level. The red and white boxes highlight the CLLJ domain (13°–17°N, 80°–70°W), whereas the black contours indicate a ratio of 1, indicating similar degrees of change between SST and T300 and thus no particular change in stability. The variable fields used to generate this figure were sourced from the ERA5 reanalysis dataset.

Warming SSTs may be changing the conditions necessary for triggering early season convection

Caribbean SSTs (SST_{CAR}) show robust increases over the historical record for the period 1979-2024 (Fig. 2a, c), with a marked acceleration in warming from the late 1990s[20,28,29]. The average warming rate of the early season SST_{CAR} was +0.012 °C yr^{-1} over the same period, consistent with previous observations[28]. A consequence of this large-scale warming is the earlier onset of temperatures akin to late-season conditions, as illustrated in Fig. 2a using the static SST value (SST_{crit}) of 27.6 °C, which corresponds roughly to the lower limit of the Caribbean SST convective range[14,29]. Other choices of SST_{crit} within the convective range showed similar trends (Table S1). With robust increases beyond the SST convective threshold, the early season environment now attains SSTs typical of the late season and is capable of supporting intense convection. This was particularly evident with 2024 and Hurricane Beryl, which became the earliest major hurricane (category 3 or higher) in the Atlantic and the earliest category 4 hurricane in June.

However, in the early season, precipitation does not show any significant change in its onset and in fact, shows an overall decline with a drying rate of −0.008 mm day^{-1} yr^{-1} (Fig. 2b, d). This suggests that surface warming trends are not the only factor to consider in the delayed onset of early season rainfall. One likely explanation is increased atmospheric stability; that is, although SSTs routinely exceed the convective threshold, a more stable atmosphere may be emerging, which inhibits rainfall development and weakens the SST-rainfall link.

To investigate this, we examine the early-season convective available potential energy (CAPE), convective inhibition (CIN), and 300-hPa temperature (T300) over the region (Fig. 3a–c). For rising air parcels, CAPE indicates how favorable the environment is for convection by measuring the amount of energy available, whereas CIN indicates the amount of energy needed to initiate convection. These variables provide a general idea of the state of atmospheric stability. Figures 3a, b suggest that the tropical North Atlantic is trending towards increased atmospheric stability, with decreasing CAPE and increasing CIN over the central and eastern Caribbean region. The Gulf of Mexico shows an increasing trend in CAPE with no robust change in CIN, suggesting greater instability in the northwestern North Atlantic region. The increasing CAPE trends in the Gulf of Mexico are somewhat consistent with the regions of increasing rainfall (and smaller changes in CIN). Similar trends were observed for 700-hPa relative humidity (Fig. S2). This spatial divergence in atmospheric stability could lead to increased heterogeneity in rainfall responses across the Caribbean, potentially complicating regional forecasting and seasonal climate prediction efforts.

The stabilizing trends in CAPE and CIN across the Caribbean are consistent with warming of the upper troposphere. Recent studies have observed that warming aloft greatly determines stability trends and, consequently, the convective threshold across the tropics[21]. Figure 3c illustrates the trends in 300-hPa air temperatures and shows that the upper atmosphere is warming at rates comparable to those at the surface. However, there are notable spatial differences in warming compared to the surface and aloft, resulting in contrasting trends in atmospheric stability across the region (Fig. 3d). When the rate of warming at the surface is contrasted with the rate of warming aloft, we see that the Caribbean precipitation trend is led by the warming aloft, consistent with greater stability, while regions to the northwest have little to no change in their stability state (Fig. 3d). Increased atmospheric stability over the eastern Caribbean may have implications for regional climate dynamics, as the strongest trends occurred close to the center of the CLLJ (Fig. 3d).

Indications of an increasingly stable atmosphere can also be observed during the dry season, where changes in not only SSTs but upper-tropospheric temperatures have been more pronounced and, to a lesser extent, the late rainfall season (Fig. S2a, d, g, j). This trend is likely due to the NASH's intensification, which has extended further west since the late 1970s[30,31]. The intensification of NASH promotes subtropical anticyclonic

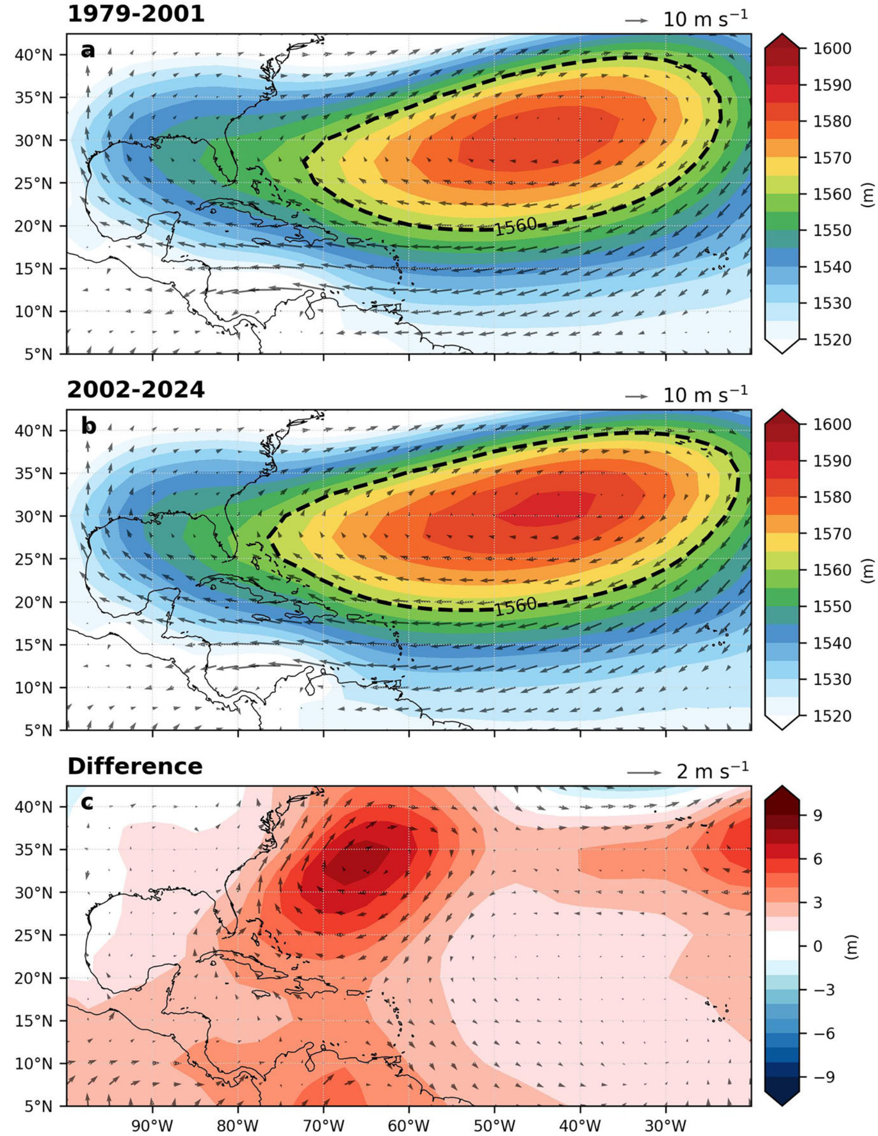

Fig. 4 | Increased low-level geopotential heights due to intensified North Atlantic subtropical high. May–July mean 850-hPa geopotential heights (m, shaded contours) and 925-hPa horizontal wind speeds ($m\ s^{-1}$, quivers) averaged over **a** 1979–2001 and **b** 2002–2024. Dashed contours indicate the 1560-gph contour line and highlight the westward extension of the North Atlantic Subtropical High (NASH). The 2002–2024 minus 1979–2001 difference in the mean variables is shown in (**c**). The statistical significance of long-term changes in geopotential heights and circulation is shown in Fig. S3.

flow to the east of the US east coast that increases the geopotential height over the basin (Fig. S2a), which extends into the central Caribbean. The poleward-moving side of the anticyclone strengthens the northward moisture flux over the Gulf of Mexico and western Caribbean (Fig. S4), whereas the equatorward-moving arm of this anticyclonic flow suppresses the usual northward influx of moisture over the eastern Caribbean (Fig. 4c). This results in a moisture dipole[32]. Therefore, these changes in NASH result in more persistent dry season conditions that currently sustain, if not intensify, the CLLJ, which normally would have weakened by the early season's onset.

The trends in the late-season environmental conditions are in stark contrast to the dry and early rainfall seasons. In recent years, the late season has been characterized by increasingly favorable conditions, consistent with projected decreases in North Atlantic vertical wind shear with warming and more intense convective activity[33,34]. Differential warming between the central Caribbean SSTs and temperatures aloft was much weaker than that in the dry and early seasons. A suppressed late-season CLLJ reduces vertical wind shear and promotes increased rainfall. Additionally, the subtropical anticyclonic flow was greatly reduced owing to the weakened and receding NASH (Fig. S3c), allowing for an increased eastward influx of moisture from the equatorial Atlantic into the region (Fig. S3i). The trends indicate an increasing contrast in Caribbean seasonal rainfall variability, with reduced rainfall activity in the first half of the year but intensifying rainfall activity towards the end.

Shifting dynamics

We further explored the influence of warming on regional climate dynamics by examining changes in regional moisture flux and low-level wind speeds and their impact on the CLLJ. Notably, the strongest early season trends in atmospheric stability were observed near the core domain of the CLLJ (13°–17°N, 80°–70°W; see again Fig. 3d), suggesting a potential link between enhanced low-level winds and suppressed convection. The CLLJ typically exhibits two seasonal peaks, in February and July, which coincide with the Caribbean dry season and MSD, respectively[6,7]. This seasonal behavior influences moisture transport and vertical wind shear in the Caribbean Basin.

Trends in North Atlantic 925-hPa zonal wind speeds are strongest and most significant in the dry season and particularly in the subtropical North Atlantic (Fig. S4). There are also indications of earlier intensification, potentially beginning as early as April, although these trends are not yet statistically robust (Fig. S4). A stronger CLLJ suppresses early season rainfall by enhancing subsidence and promoting the advection of dry air from the subtropics[8]. These findings suggest that zonal wind patterns may now play a more prominent role in modulating rainfall onset than SST alone.

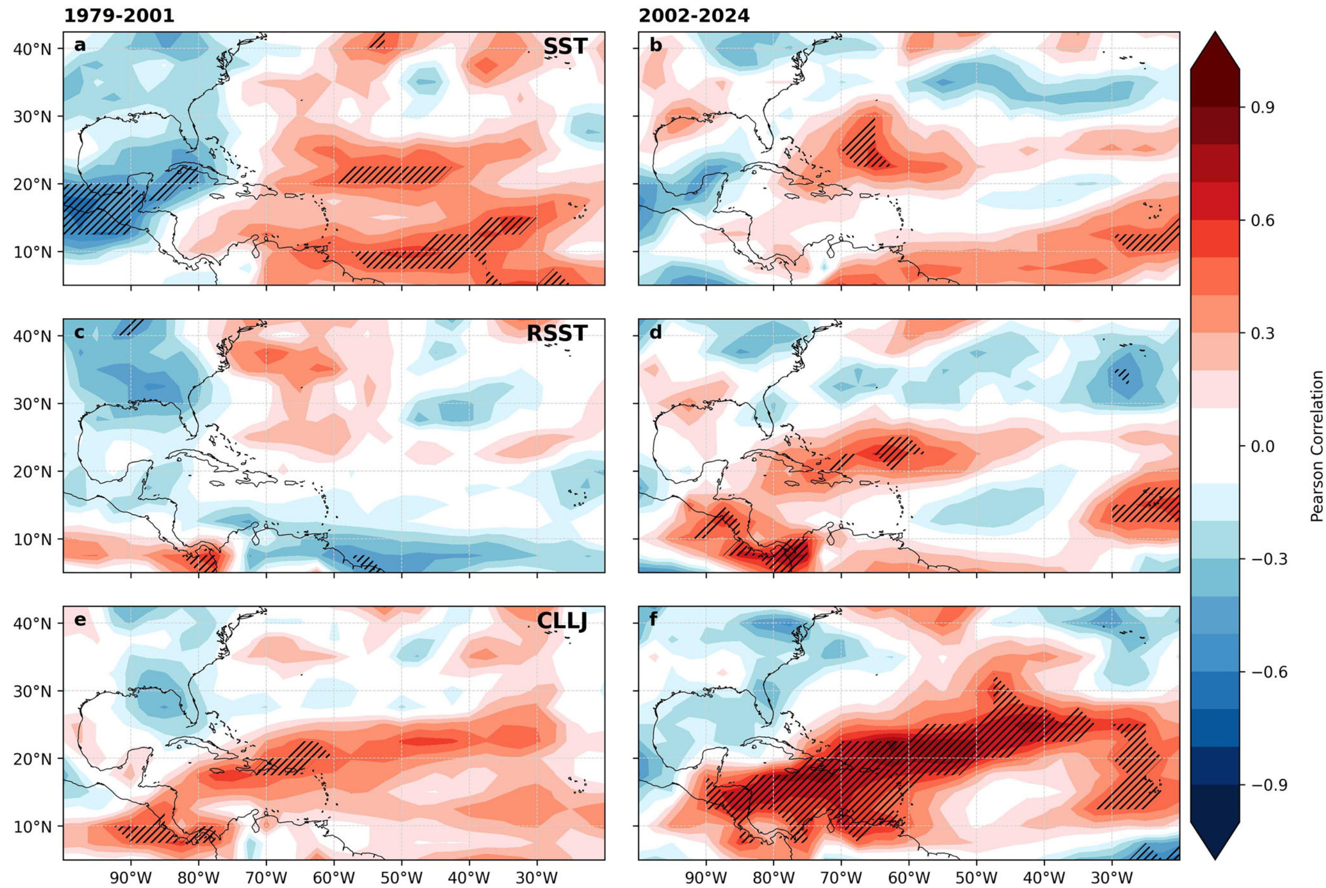

Fig. 5 | Changing correlations between low-level relative humidity and SSTs, RSSTs and the CLLJ over time. Correlation maps between Caribbean the early-season 700-hPa relative humidity field and May–July indices of **a**, **b** Caribbean sea surface temperature (SST_{CAR}); **c**, **d** Caribbean SSTs relative to the equatorial eastern Pacific ($RSST_{CAR}$), and the CLLJ **e**, **f** for time periods 1979–2001 (left panels) and 2002–2024 (right panels).

As described initially, the northward flow during May-July advects moisture from the deep tropical eastern Pacific into the Caribbean region resulting in enhanced precipitation. However, trends in the northward moisture flux show enhanced moisture flux over the western Caribbean but reduced northward flux over the eastern Caribbean due to the increased westward extension of the NASH and thus increased southward flow (Fig. S4). The reduction in northward moisture flux suppresses early season rainfall and promotes a longer dry season and, hence, a prolonged CLLJ over the eastern Caribbean region.

These trends suggest that, for the Caribbean early rainfall season, variability in the low-level easterlies is strengthening as a key indicator for the onset of rainfall. In Fig. 5, we correlated the May–July mean indices of SST_{CAR}, $RSST_{CAR}$, and the CLLJ to the May–July 700-hPa relative humidity field at each grid point during the time periods of 1979–2001 and 2002–2024. Relative humidity is used here as a moisture indicator of the early rainfall season onset[11].

During 1979-2001, early-season Caribbean RH700 were mostly positively correlated with SSTs in the central and eastern Caribbean (~+0.3) and negatively correlated (~−0.4) with those in the western Caribbean (Fig. 5a). RH700 correlations with $RSST_{CAR}$ were negative with little significance in the domain (Fig. 5c), likely due to a weak zonal gradient between the eastern Pacific and North Atlantic basins relative to the more recent time period[35]. The CLLJ was positively correlated with RH700 (~+0.5) in the central Caribbean (Fig. 5e). During 2002–2024, SST_{CAR} correlations weaken (−0.3 in the western Caribbean and +0.1 in the central/eastern Caribbean) relative to $RSST_{CAR}$ and CLLJ (Fig. 5b, d, f). The $RSST_{CAR}$ correlations were stronger and positive, consistent with strengthened zonal SST gradients owing to warm Atlantic-cool Pacific SST trends[35]. Among the three indices, the CLLJ was the strongest predictor in both time periods, but seemingly outstrips SST_{CAR} and $RSST_{CAR}$ in the latter time period.

Discussion

The early rainfall season in the Caribbean is vital for replenishing water resources following the dry season and for supporting early agricultural activities ahead of the mid-summer drought[36]. Historically, SST variability in the Caribbean and tropical North Atlantic has served as a reliable predictor of early season rainfall, as it determines whether conditions exceed the convective threshold (SST_{crit}) required to initiate deep convection. SSTs in the tNA have increased significantly, particularly over the past few decades. The findings presented in this study suggest that recent warming has caused SST_{crit} to be reached earlier in the year, corresponding to a more expansive AWP during MJJ. While this shift means that the early season can now support intense convective events, as exemplified by Hurricane Beryl in June 2024, it simultaneously weakens the historical SST-rainfall relationship and raises concerns about the continued reliability of static SST-based rainfall predictors during this period.

The findings of this study further show that the warming SSTs and earlier attainment of SST_{crit} have not led to earlier or increased rainfall in some regions of the Caribbean. Instead, the region exhibited increased atmospheric stability, as evidenced by the declining CAPE and rising CIN. This suggests that, on average, the atmosphere over the eastern Caribbean and wider tNA is becoming less conducive to deep convection, even as SSTs warm.

This apparent paradox—warmer SSTs coinciding with reduced rainfall—can be explained by differential warming between the surface and the upper troposphere. The upper troposphere warms at a faster rate than the surface, leading to an increase in static stability. This enhanced stability suppresses vertical motion and delays the onset of convection, thereby reducing rainfall. Additionally, warming trends over the historical period have forced the NASH to intensify and extend further west, imposing an anticyclonic flow over the Caribbean. This forced anticyclonic flow reduced the northward moisture flux within the vicinity of the CLLJ, allowing the easterlies and positive geopotential heights to persist over the region during MJJ.

The above results are in line with projected drying within the Caribbean under global warming. Under the worst-case warming scenarios, Caribbean rainfall is substantially reduced by as much as 50% across the entire region and in all seasons[15,37–39]. Projected El Niño-like warming in the equatorial Pacific increases the westward zonal flow and deep-layer vertical wind shear; low-level relative humidity is reduced as more dry air is advected into the region. These conditions ultimately result in the intensification and increased persistence of the CLLJ.

However, the drying trend observed in recent years occurs despite the progressively warmer Atlantic and cooler equatorial eastern Pacific background state[35], the combination of which should produce regional-scale ascent and rainfall[18,40]. In this case, drying is driven by a different mechanism, namely, the intensification and westward extension of the NASH, which suppresses rainfall over the eastern Caribbean. Stronger suppression over the region is likely kept at bay by the equatorial Pacific's La Niña-like cooling, driving ascent over the western Caribbean[32]. Furthermore, current state-of-the-art models still struggle to adequately capture equatorial Pacific cooling under present warming conditions, further complicating the relationship between SST variability and rainfall activity throughout the tNA[39,41]. Some studies suggest that Pacific cooling is transient in nature[41]. In the case of a switch to a more El Niño-like background state, the western Caribbean and Gulf of Mexico regions are likely to begin drying.

The above findings highlight the growing importance of dynamic and thermodynamic variables—beyond absolute SSTs—in predicting early-season rainfall. Research suggests relative SSTs (local SSTs minus the tropical mean) as a robust indicator of atmospheric instability[23], accounting for the broader warming context and being better correlated with convective activity. Our results show that $RSST_{CAR}$ has become increasingly correlated with early-season rainfall, even though the SST-rainfall relationship has weakened (Fig. 4). However, trends in relative SSTs during the early rainfall season showed little to no increase, suggesting that the regional environment was not becoming more favorable for convection despite rising absolute SSTs.

The Caribbean appears to be entering a new era in which traditional SST-based predictors of early season rainfall have become increasingly unreliable. Although SSTs in the tropical North Atlantic continue to rise, this warming no longer results in increased rainfall. Instead, enhanced atmospheric stability, driven by upper tropospheric warming and an intensifying NASH, and the persistence of dry-season conditions, including the CLLJ, are emerging as key modulators of rainfall suppression.

The weakening correlation between absolute SSTs and early-season rainfall underscores the need to reconsider the foundational assumptions of seasonal prediction frameworks. Our findings show that relative SSTs and dynamic atmospheric variables, such as low-level wind strength, now provide stronger explanatory power than SST magnitude alone.

These results contribute to a growing body of evidence across the tropics that warming is disrupting conventional rainfall predictors. This shift has profound implications for seasonal climate forecasting, especially for Caribbean Small Island Developing States (SIDS), which depend heavily on early season rainfall for agriculture, water security, and disaster preparedness.

Policymakers, forecasters, and regional climate institutions must adapt to these changing dynamics by integrating updated predictors into operational forecast systems and long-term adaptation planning. Future research should prioritize the refinement of relative SST indices, atmospheric stability diagnostics, and circulation-based metrics to ensure more robust rainfall projections in a warming world.

Methods

Data sources

This study employed a suite of observational and reanalysis datasets to investigate the relationship between precipitation (PRECIP) variability in the Caribbean region and sea surface temperatures (SSTs) in the tropical North Atlantic (tNA). For the observed trends in SSTs and PRECIP, the Extended Reconstructed Sea Surface Temperature version 5 (ERSSTv5) dataset and Global Precipitation Climatology Project (GPCP) monthly analysis were used. ERSSTv5 provides global monthly SSTs based on the International Comprehensive Ocean-Atmosphere Dataset (ICOADS) with a spatial resolution of $2° \times 2°$ and temporal coverage from January 1854 to the present[42]. The GPCP is a temporally and spatially consistent $2.5° \times 2.5°$ dataset of monthly rainfall fields from January 1979 to the present, comprising satellite data, rain-gauge station data, and sounding observations[43]. For atmospheric variables, including 925-hPa zonal wind speeds, convective available potential energy, convective inhibition, and 300-hPa air temperatures, the fifth-generation ECMWF reanalysis (ERA5) dataset was used. ERA5 data are available from January 1940 to the present and have a native horizontal resolution of $0.25° \times 0.25°$ [44,45]. The data were further coarsened to a $2.5° \times 2.5°$ grid resolution to be comparable with the observations.

Climate Indices

The Caribbean region is defined as 5°–25°N and 90°–60°W[1], whereas the tNA domain is defined as 5°–25°N and 80°–15°W. The Caribbean low-level jet index (CLLJ) is defined as the 925-hPa zonal wind speed averaged over the domain 13°–17°N and 80°–70°W[6,7,12]. The zonal SST gradient ($RSST_{CAR}$) is defined as the difference between Caribbean SSTs (SST_{CAR}) and equatorial eastern Pacific SSTs in the Niño-3.4 region (5°S–5°N, 170°–120°W)[4,16,18,37,40].

The SST convective threshold

The SST convective range for the Caribbean region is defined as 27°–29 °C[14,28,29], and the static convective threshold is defined as 27.6 °C, corresponding to 3.5 mm day^{-1} based on the SST-rainfall relationships plotted in Fig. 1.

Linear trends

The statistical significance of linear trends over time was determined using the non-parametric Mann-Kendall test for monotonic trends. The test was performed using the PyMannKendall Python package[46]. The strength of the other linear relationships was determined using ordinary least squares methods.

Data availability

Global Precipitation Climatology Project (GPCP) Monthly Analysis Product data is provided by the NOAA PSL, Boulder, Colorado, USA, from their website at https://psl.noaa.gov/data/gridded/data.gpcp.html. NOAA's ERSSTv5 is available at https://psl.noaa.gov/data/gridded/data.noaa.ersst.v5.html. Other gridded atmospheric data was obtained from the fifth generation ECMWF reanalysis (ERA5) and is publicly available at https://cds.climate.copernicus.eu/.

Code availability

The data and underlying code used to generate the manuscript figures are publicly available for download via Github (https://github.com/jhordannej/breaking-the-caribbean-SST-rainfall-link) and Zenodo (https://doi.org/10.5281/zenodo.16468534).

Received: 27 July 2025; Accepted: 7 January 2026;
Published online: 19 January 2026

References

1. Climate Studies Group Mona (eds). State of the Caribbean Climate (2020). Produced for the Caribbean Development Bank https://www.

caribank.org/publications-and-resources/resource-library/publications/state-caribbean-climate (2020).
2. Forde, M. S., Cashman, A. & Mitchell, K. Sustainability of water resources in Caribbean small island developing states: an overview. *Discov. Sustain.* **5**, 265 (2024).
3. Giannini, A., Kushnir, Y. & Cane, M. A. Interannual variability of Caribbean rainfall, ENSO, and the Atlantic Ocean. *J. Clim.* **13**, 297–311 (2000).
4. Taylor, M. A., Enfield, D. B. & Chen, A. A. Influence of the tropical Atlantic versus the tropical Pacific on Caribbean rainfall. *J. Geophys. Res.: Oceans* **107**, 10–1–10–14 (2002).
5. Ashby, S. A., Taylor, M. A. & Chen, A. A. Statistical models for predicting rainfall in the Caribbean. *Theor. Appl. Climatol.* **82**, 65–80 (2005).
6. Wang, C. Variability of the Caribbean low-level jet and its relations to climate. *Clim. Dyn.* **29**, 411–422 (2007).
7. Whyte, F. S., Taylor, M. A., Stephenson, T. S. & Campbell, J. D. Features of the Caribbean low level jet. *Int. J. Climatol.: A J. R. Meteorol. Soc.* **28**, 119–128 (2008).
8. Cook, K. H. & Vizy, E. K. Hydrodynamics of the Caribbean low-level jet and its relationship to precipitation. *J. Clim.* **23**, 1477–1494 (2010).
9. Gouirand, I., Moron, V. & Sing, B. Seasonal atmospheric transitions in the Caribbean basin and Central America. *Clim. Dyn.* **55**, 1809–1828 (2020).
10. Neelin, J. D., Peters, O. & Hales, K. The transition to strong convection. *J. Atmos. Sci.* **66**, 2367–2384 (2009).
11. Allen, T. L. & Mapes, B. E. The late spring Caribbean rain-belt: climatology and dynamics. *Int. J. Climatol.* **37**, 4981–4993 (2017).
12. Martinez, C., Goddard, L., Kushnir, Y. & Ting, M. Seasonal climatology and dynamical mechanisms of rainfall in the Caribbean. *Clim. Dyn.* **53**, 825–846 (2019).
13. Lau, K., Wu, H. & Bony, S. The role of large-scale atmospheric circulation in the relationship between tropical convection and sea surface temperature. *J. Clim.* **10**, 381–392 (1997).
14. Folkins, I. & Braun, C. Tropical rainfall and boundary layer moist entropy. *J. Clim.* **16**, 1807–1820 (2003).
15. Martinez, C., Kushnir, Y., Goddard, L. & Ting, M. Interannual variability of the early and late-rainy seasons in the Caribbean. *Clim. Dyn.* **55**, 1563–1583 (2020).
16. Enfield, D. B. & Alfaro, E. J. The dependence of Caribbean rainfall on the interaction of the tropical Atlantic and Pacific Oceans. *J. Clim.* **12**, 2093–2103 (1999).
17. Spence, J. M., Taylor, M. A. & Chen, A. A. The effect of concurrent sea-surface temperature anomalies in the tropical Pacific and Atlantic on Caribbean rainfall. *Int. J. Climatol.* **24**, 1531–1541 (2004).
18. Taylor, M. A., Stephenson, T. S., Owino, A., Chen, A. A. & Campbell, J. D. Tropical gradient influences on Caribbean rainfall. *J. Geophys. Res. Atmos.* **116**, https://doi.org/10.1029/2010JD015580 (2011).
19. Jones, J. J., Bell, M. M. & Klotzbach, P. J. Tropical and subtropical North Atlantic vertical wind shear and seasonal tropical cyclone activity. *J. Clim.* **33**, 5413–5426 (2020).
20. Hibbert, K., Glenn, E., Smith, T. M. & González-Cruz, J. E. Changes to sea surface temperatures and vertical wind shear and their influence on tropical cyclone activity in the Caribbean and the main developing region. *Atmosphere* **14**, 999 (2023).
21. Johnson, N. C. & Xie, S.-P. Changes in the sea surface temperature threshold for tropical convection. *Nat. Geosci.* **3**, 842–845 (2010).
22. Evans, J. L. & Webster, C. C. A variable sea surface temperature threshold for tropical convection. *Aust. Meteorol. Oceanogr. J.* **64**, S1–S8 (2014).
23. Izumo, T., Vialard, J., Lengaigne, M. & Suresh, I. Relevance of relative sea surface temperature for tropical rainfall interannual variability. *Geophys. Res. Lett.* **47**, e2019GL086182 (2020).
24. Hollis, M. A., McCrary, R. R., Stachnik, J. P., Lewis-Merritt, C. & Martin, E. R. A global climatology of tropical easterly waves. *Clim. Dyn.* **62**, 2317–2332 (2024).
25. Bercos-Hickey, E. & Patricola, C. M. African easterly wave strength and observed atlantic tropical cyclone genesis and characteristics. *J. Geophys. Res. Atmos.* **129**, e2024JD040858 (2024).
26. Bercos-Hickey, E. & Patricola, C. M. Drivers of Atlantic Tropical Cyclogenesis: African Easterly Waves and the Environment. *Geophys. Res. Lett.* **52**, e2024GL112002 (2025).
27. He, C. et al. Tropical Atlantic multidecadal variability is dominated by external forcing. *Nature* **622**, 521–527 (2023).
28. Glenn, E., Comarazamy, D., González, J. E. & Smith, T. Detection of recent regional sea surface temperature warming in the Caribbean and surrounding region. *Geophys. Res. Lett.* **42**, 6785–6792 (2015).
29. Glenn, E. et al. Tropical convection in the Caribbean and surrounding region during a regional, warming sea-surface temperature period, 1982–2020. *Hydrology* **8**, 56 (2021).
30. Li, W., Li, L., Fu, R., Deng, Y. & Wang, H. Changes to the North Atlantic subtropical high and its role in the intensification of summer rainfall variability in the southeastern United States. *J. Clim.* **24**, 1499–1506 (2011).
31. Li, W., Li, L., Ting, M. & Liu, Y. Intensification of northern hemisphere subtropical highs in a warming climate. *Nat. Geosci.* **5**, 830–834 (2012).
32. Bregy, J. C., Maxwell, J. T., Robeson, S. M., Harley, G. L. & Trouet, V. Changes in the western flank of the North Atlantic subtropical high since 1140 ce: Extremes, drivers, and hydroclimatic patterns. *Sci. Adv.* **11**, eadr5065 (2025).
33. Ting, M., Kossin, J. P., Camargo, S. J. & Li, C. Past and future hurricane intensity change along the US East coast. *Sci. Rep.* **9**, 7795 (2019).
34. Balaguru, K. et al. Increasing hurricane intensification rate near the US Atlantic coast. *Geophys. Res. Lett.* **49**, e2022GL099793 (2022).
35. Chung, E.-S. et al. Tropical eastern Pacific cooling trend reinforced by human activity. *npj Clim. Atmos. Sci.* **7**, 170 (2024).
36. Gamble, D. W. et al. Climate change, drought, and Jamaican agriculture: local knowledge and the climate record. *Ann. Assoc. Am. Geogr.* **100**, 880–893 (2010).
37. Taylor, M. A., Whyte, F. S., Stephenson, T. S. & Campbell, J. D. Why dry? Investigating the future evolution of the Caribbean Low Level Jet to explain projected Caribbean drying. *Int. J. Climatol.* **33**, https://doi.org/10.1002/joc.3461 (2013).
38. Taylor, M. A. et al. Future Caribbean climates in a world of rising temperatures: the 1.5 vs 2.0 dilemma. *J. Clim.* **31**, 2907–2926 (2018).
39. Brotons, M., Haarsma, R., Bloemendaal, N., De Vries, H. & Allen, T. Drivers of Caribbean precipitation change due to global warming: analyses and emergent constraint of CMIP6 simulations. *Clim. Dyn.* **62**, 3395–3415 (2024).
40. Clarke, L. A. *Caribbean Precipitation Variability: Another Look at Its Relationship With the Tropical Atlantic-Pacific SST Gradient.* Ph.D. thesis. Accessed at https://uwin-primo.hosted.exlibrisgroup.com/permalink/f/18djlrd/STA_ALEPH000399061 (2015).
41. Sobel, A. H. et al. Near-term tropical cyclone risk and coupled earth system model biases. *Proc. Natl. Acad. Sci. USA* **120**, e2209631120 (2023).
42. Huang, B. et al. Extended reconstructed sea surface temperature, version 5 (ERSSTv5): upgrades, validations, and intercomparisons. *J. Clim.* **30**, 8179–8205 (2017).
43. Adler, R. F. et al. The version-2 global precipitation climatology project (GPCP) monthly precipitation analysis (1979–present). *J. Hydrometeorol.* **4**, 1147–1167 (2003).
44. Hersbach, H. et al. The ERA5 global reanalysis. *Q. J. R. Meteorol. Soc.* **146**, 1999–2049 (2020).

45. Hersbach, H. et al. ERA5 hourly data on single levels from 1940 to present, Copernicus Climate Change Service (C3S) Climate Data Store (CDS) https://doi.org/10.24381/cds.adbb2d47 (2023).
46. Hussain, M. & Mahmud, I. pyMannKendall: a Python package for non-parametric Mann-Kendall family of trend tests. *J. Open Source Softw.* **4**, 1556 (2019).

Author contributions

Conceptualization: L.C., M.T., T.S. Methodology: L.C., J.J., M.T. Investigation: L.C., J.J., M.W., T.E. Visualizations: J.J., L.C., M.W., T.E. Writing—original draft: All authors. Writing—review & editing: All authors. All authors have read and approved the final version of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41612-026-01325-8.

Correspondence and requests for materials should be addressed to Jhordanne J. Jones.