

Spatiotemporal analysis of compound hot-dry and hot-wet extreme events over Tanzania

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Abstract

Although there is growing literature on single-variable extremes (drought, heavy rainfall, heatwaves), there are limited studies that explicitly examine compound hot–wet and hot–dry events across Tanzania. This study investigated the spatiotemporal characteristics and drivers of compound hot–dry and hot–wet extreme events across Tanzania during 1981–2023. Using the Climatic Research Unit dataset, compound extremes were identified based on concurrent anomalies in monthly temperature and precipitation exceeding the 75th percentile and falling below the 25th percentile thresholds, respectively. The results show pronounced spatial and seasonal variability. Hot-wet extremes are predominantly observed in central and southern regions, with a peak during the March-May (MAM) long rains, while hot–dry extremes are more frequent across the northern and western areas, intensifying during the October-December (OND) short rains. Both hot-wet and hot-dry events have intensified over recent decades, suggesting growing climatic risks. Trend analyses indicate significant increases in hot-wet frequencies during OND and June to September (JJAS), and in both hot-wet and hot-dry during the extended wet and climatologically dry JJAS seasons. Analysis of large-scale oceanic drivers reveals a dominant and nonlinear synergistic influence from the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). Composite and correlation analyses show that hot-wet extremes are strongly associated with El Niño and positive IOD phases, while hot-dry extremes coincide with La Niña and negative IOD conditions. The concurrent positive ENSO–IOD phases produce the most widespread hot-wet anomalies, explaining up to 62% of the interannual variance in hot-wet events during the January–February season. These findings highlight the increasing frequency of compound climate extremes in Tanzania and reveal substantial predictability linked to large-scale oceanic variability. The significant multi-month lagged correlations demonstrate promising potential for integrating compound-event diagnostics into subseasonal-to-seasonal forecasting and early warning systems.

1. Introduction

Extreme weather events, particularly heatwaves and heavy rainfalls, are increasingly recognized as major challenges to socio-economic development and environmental sustainability in Sub-Saharan Africa (Ayanlade et al. 2022; Lim Kam Sian et al. 2024; Maino and Emrullahu 2022; Weber et al. 2018). Tanzania, like much of the Sub-Saharan region, is experiencing heightened vulnerability to these extremes due to its dependence on climate-sensitive sectors, including agriculture, water resources, health, and infrastructure. Under the global warming fingerprint, coupled with regional climatic variability, the frequency and intensity of compound climate extremes, such as heatwaves and heavy rainfall, are amplifying (Vogel et al. 2020; Luhunga 2022; Biess et al. 2024; Omay et al. 2024; Wei et al. 2024). Indeed, CMIP6 climate model projections confirm that tropical Africa, including Tanzania, is likely to experience a significant increase in the frequency and intensity of compound extremes (Vogel et al. 2020). This can bring devastating implications to agriculture, water resources and ecosystems, eventually leading to the food deficit in Tanzania. Therefore, understanding the characteristics of compound extreme events and associated drivers is essential for informing mitigation measures and adaptation strategies across the country.

Existing studies have indicated that, in East Africa, where Tanzania is located, shifts in rainfall regimes and rising temperatures are manifesting in both prolonged dry spells and episodes of excessive rainfall, often within the same season (Taye and Dyer 2024). The 2019–2020 Lake Victoria floods demonstrate how extreme heat can amplify the effects of heavy rainfall, emphasizing the compounding and interconnected nature of climate extremes in the region. Similarly, recent assessments indicate that parts of northern Tanzania and areas surrounding Lake Victoria are experiencing compound hot-dry extremes of moderate to severe magnitude (Ayugi et al. 2024), underscoring the urgent need to investigate the spatial and temporal interactions of these extremes. Moreover, future projections suggest intensifying wet and dry extremes. Seasonal rainfall is expected to increase by 10–20%, especially during the October–December (OND) and March–May (MAM) seasons, with more extended wet spells (Omay et al. 2024). Conversely, dry spells are projected to become more frequent during the June–September (JJAS) season, exacerbating drought risks. The mechanistic explanations for these seasonal changes are associated with the large-scale climate drivers such as the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) (Chobo and Huo, 2024). Positive IOD phases and El Niño conditions have been associated with extreme precipitation and increased flood risks, while La Niña phases typically lead to droughts and heatwaves (Taye and Dyer 2024). Notably, even in neutral ENSO years, anthropogenic climate change is increasingly found to drive the co-occurrence of extreme heat and rainfall across East Africa (Vogel et al. 2020).

Despite the expanding literature on climate extremes, there is still a notable knowledge gap regarding compound hot-dry and hot-wet extreme events in Tanzania, particularly in terms of their frequency, drivers, and impacts across different regions and seasons. Most existing studies have treated heatwaves, droughts, and floods as discrete phenomena, with limited attention to their concurrent or sequential manifestations (Zscheischler et al. 2018; Leonard et al. 2014; Seneviratne et al. 2012). Moreover, the spatial and temporal dynamics of these compound events, including their frequency and specific drivers across the country, remain insufficiently understood. Therefore, this study aims to address this gap by conducting a spatiotemporal analysis of compound hot-dry and hot-wet extremes over Tanzania. Specifically, it seeks to: (1) quantify the frequency and distribution of these compound events; and (2) examine to what extent the oceanic drivers influence the occurrence and intensity of the events. The findings are expected to provide critical insights for climate adaptation planning, risk management, and policy formulation in Tanzania and the broader East African region. This study is organized as follows: Section 2 describes the study area, data, and methods; Section 3 covers the results and discussion, and Section 4 presents the conclusion.

2. Study area, data, and methods

2.1 Study area

Tanzania is located in East Africa, extending from approximately 28° E to 41° E longitude and 0° to 12° S latitude. The country exhibits a complex and diverse topography (Fig. 1a), ranging from low-lying coastal plains in the east to highland regions in the northeast and southern parts. This variation in elevation

contributes significantly to the spatial heterogeneity of climatic conditions across the country. The seasonal precipitation cycle is largely governed by the south–north oscillation of the Intertropical Convergence Zone (ITCZ) (Borhara et al. 2020). The seasonal migration of the ITCZ is mainly responsible for the bimodal precipitation distribution in the northern coast, northeastern highlands and areas around the Lake Victoria basin and unimodal precipitation patterns in central, southern highlands and southern areas of the country. This orientation forms three major corresponding agriculture seasons of OND and MAM for the bimodal pattern and November to April for the unimodal pattern (Borhara et al. 2020). This seasonal precipitation distribution causes most parts of the country to generally experience a wet season (October-May) and dry season JJAS.

Spatial pattern of annual precipitation varies by an order of magnitude across Tanzania, from over 90 mm in the southern and southern highlands parts to less than 40 mm in the central parts of the country (Fig. 1b). This indicates that the southwestern highlands, coastal belt, western region, and the Lake Victoria basin receive the highest average precipitation. In contrast, the central plateau and parts of the northeastern highlands experience relatively drier conditions. Similarly, temperature distribution indicates that coastal and western lowlands are climatologically warmer than the high-altitude regions in the northeast and southwest (Fig. 1c).

Annual monthly climatology reveals that the wet season corresponds with the warmest period of the year from October through to May (Fig. 1d). During this time, the country receives an average monthly precipitation exceeding 40 mm, with local peaks in December and March. The distribution of temperature climatology compliments the rainfall seasonal pattern clearly, but with earlier local peaks in October through to November.

2.2 Data

This study used the Climatic Research Unit gridded Time Series v4 (CRU TS) monthly temperature and precipitation data, and global mean monthly sea surface temperature data for the period 1961–2023. CRU TS v4 data is a widely used climate dataset derived from ground observations on a spatial resolution of $0.5^\circ \times 0.5^\circ$ grid, providing data over all land domains across the globe except over Antarctica (Harris et al. 2020). The CRU TS data have been extensively used to study the temperature and precipitation extremes over the East Africa region and in Tanzania (Dufatanye et al. 2024, Makula and Zhou 2022, Massawe and Xiao, 2020).

To investigate the influence of the sea surface temperatures (SST) on the observed frequency of the compound extremes over Tanzania, this study used the Centennial in situ Observation-Based Estimates Sea Surface temperature (COBE-SSTs). COBE-SSTs are globally observed SSTs interpolated to $1^\circ \times 1^\circ$ grid, the data spans from 1891 to date (Schneider et al., 2013). Furthermore, the study used the ENSO (Niño3.4 index) and IOD [Dipole Mode index (DMI)] to investigate their relationship with the frequency of the compound hot-wet and hot-dry events. The monthly Niño3.4 index was computed using an area-averaging of SST over the tropical eastern Pacific Ocean ($5^\circ \text{ S} - 5^\circ \text{ N}$, $170^\circ - 120^\circ \text{ W}$) based on the HadISST (Rayner et al. 2003). The index was obtained from NOAA Physical Science Laboratory. Based

on Saji et al. (1999), the DMI is defined as the difference between the SST over the western (50°-70° E, 10° S – 10° N) and southeastern (90°-110° E, 10° S – 0°) tropical Indian Ocean.

2.3 Methods

In this study, the monthly extremes in precipitation and temperature were determined using the 25th and 75th percentiles. A similar approach has been adopted in previous studies on compound extreme events, which focused on both global and regional scales (Dong et al. 2025; Peng et al. 2023; Wu et al. 2019; Hao et al. 2018). Wet (dry) events were identified for months in which precipitation exceeded the 75th percentile or fell below the 25th percentile, respectively. Hot events were defined as months with maximum temperature values above the 75th percentile. Compound events were classified when hot and wet or hot and dry conditions occurred simultaneously within the same month. (Hao et al. 2018). The analysis focuses on four climatologically distinct seasons: the transitional wet season (January–February; JF), the long rains (March–May; MAM), the dry season (June–September; JJAS), and the short rains (October–December; OND). To ensure consistency and comparability across temporal scales, all datasets were seasonally aggregated, such that the resulting analyses represent mean conditions and event frequencies within each of the four seasons. Specifically, seasonal values were computed by averaging all monthly values within each season for every year.

Composite analysis of the difference in the occurrence of the compound extremes during the positive phase and negative phase of IOD and ENSO were analyzed and compared with the regression and correlation analysis to examine the role of tropical SST variability in the Indian and Pacific Ocean to the occurrences of compound extremes. The credibility of the composite method lies on its ability to identify potential nonlinear features of climate anomalies.

3. Results and Discussion

3.1 Spatial and temporal variations of the compound extreme hot-wet and hot-dry events

Figure 2 depicts the spatial distributions of the hot-wet and hot-dry events over Tanzania. Generally, hot-wet events are predominantly concentrated over the Lake Victoria basins, central and southern region of Tanzania, whereas hot-dry events occur more frequently in the western interior, northern coasts, and northeastern highlands. These spatial distributions are most pronounced during the extended October to May period (which encompasses both the average of both short (OND), long (MAM) rainfall seasons, and transitional season (JF). During the dry season (JJAS; Fig. 2c and 2g), a contrasting spatial pattern was observed, with hot-wet extremes predominantly concentrated over the western, southern, and Lake Victoria basin regions, whereas hot-dry extremes were mainly confined to the central parts of the country. Remarkably, the northern coast of Tanzania experienced more frequent hot-dry events (with frequencies exceeding 10% of the months) and fewer hot-wet events compared to the southern coast, consistently during both the MAM and OND seasons. This finding suggests that the southern coast is

more susceptible to the co-occurrence of hot and wet conditions during the wet season, whereas both regions exhibit an increased likelihood of hot-wet extremes (with frequencies ranging between 10–15%) during the extended dry period (JJAS).

During the extended wet season, hot-wet events peak during MAM, coinciding with the long rains. This suggests that elevated moisture availability, when coupled with anomalously high temperatures, enhances the likelihood of hot-wet extremes. In contrast, hot-dry events are most prevalent during OND, aligning with the short rains typically more variable and prone to dry spells. The boxplot analysis (Fig. 2(i)) reinforces this seasonal asymmetry, showing higher median frequencies of hot-wet events in MAM and hot-dry events in OND. During the MAM long rains, hot-wet extremes were most frequent over the southwestern highlands, central regions, and southern parts (exceeding 12% of months), while hot-dry extremes were concentrated along the northern coastal belt and western Lake Victoria basin. This pattern is fundamentally inverted during the OND short rains: The hot-wet activity shifts eastward, dominating the coasts and northeastern highlands, consistent with the climatological peak, while hot-dry extremes become prevalent across the western half of the country, encompassing the southwestern highlands and Lake Tanganyika basin (exceeding 15% of months). This distinct alternating configuration demonstrates the strong influence of seasonal atmospheric and oceanic forcing. Specifically, the MAM pattern is driven by the northward ITCZ migration, land-surface heating, and Congo Air Boundary (CAB) moisture, amplified by orographic uplift in the highlands. Conversely, the OND reversal, characterized by hot-dry events dominance in the west, is strongly linked to the westward retreat of the ITCZ and the intensifying effect of oceanic teleconnections, such as negative IOD or La Niña phases, which promote subsidence and suppress rainfall across the interior.

The JF transitional season is characterized by climatic volatility, registering the widespread occurrence of both hot-wet and hot-dry extremes across nearly all of Tanzania, reflecting a period of elevated temperatures and fluctuating moisture conditions that bridges the major rainy seasons. The hot-wet events were notably concentrated in the Lake Victoria basin, the northeastern highlands, and localized areas in Morogoro and the southern coastal regions (including Lindi and Mtwara), with frequencies exceeding 8% of the months during 1981–2023. This localized enhancement of hot-wet activity underscores the dominance of regional and mesoscale mechanisms during this transitional period. Specifically, the enhanced hot-wet events over the Lake Victoria basin is likely due to the lake-induced convection and sustained moisture fluxes, where the lake's thermal inertia and mesoscale circulations modulate the local climate even as surrounding areas may experience drier conditions. In the northeastern highlands, hot-wet events occur from the interplay between topographic uplift and residual moisture from the OND season, intensified by the region experiencing peak surface temperatures during JF, which promotes convective instability. The hot-wet pockets over Morogoro and the southern coastal regions, conversely, reflect the strong influence of warm Indian Ocean SSTs, which enhance moisture transport and convection during warm phases of regional climate variability. The persistence of these hot-wet hotspots demonstrates the heightened sensitivity of coastal and near-lake regions to coupled ocean–land–atmosphere interactions during the JF transition.

Conversely, hot-dry events during JF were more widespread, with significant coverage across western, central, and extending into the southwestern highlands of Tanzania, where frequencies exceeded 10% of the months during 1981–2023. This broad spatial extent suggests that large portions of inland Tanzania experience substantial thermal and moisture stress during JF. The dominance of hot-dry events in these regions can be associated with reduced rainfall, strong surface heating, and low soil moisture availability following the short rains and higher evapotranspiration, which together amplify land–atmosphere feedback mechanisms. The combination of high solar insolation, subsidence over central and western regions, and limited moisture advection from the Indian Ocean further supports the persistence of hot-dry extremes. A distinct though less frequent pattern emerges during the JJAS dry season. Although total rainfall is minimal across most of Tanzania, the persistence of elevated maximum temperatures leads to widespread hot-dry extremes (Fig. 2g), particularly over the central plateau, northern coast, and southwestern highlands. These regions experience prolonged sunshine and reduced cloud cover, resulting in strong surface heating and rapid soil-moisture depletion that reinforce the co-occurrence of heat and dryness. The JJAS hot-dry anomalies coincide with the southward displacement of the ITCZ and the dominance of subtropical high-pressure systems that suppress convection across much of the country. Interestingly, localized hot-wet anomalies appear along the western Lake Victoria basin and adjacent highlands even during JJAS (Fig. 2c). These events likely arise from lake-breeze convergence zones and mesoscale convective systems sustained by the warm lake surface, as observed by Chang’a et al. (2021) and Nicholson (2017). Despite being infrequent, these lake-driven hot-wet extremes demonstrate that local moisture sources can override the broader dry-season regime under favorable thermal and dynamical conditions.

These findings underscore the importance of incorporating transitional seasons and physiographic features; such as large inland water bodies into compound climate risk assessments. The spatial heterogeneity observed during JF highlights the influence of localized drivers and land–atmosphere interactions, which may not be captured by broader seasonal averages and warrant further investigation through high-resolution modeling and targeted diagnostics. The observed spatial and seasonal patterns of hot-dry and hot-wet align with projections from Luhunga (2022, 2025), who reported a statistically significant increase in temperature extremes across Tanzania. While rainfall-related extremes were projected to increase at a non-significant level, the intensification of heat extremes alone could exacerbate compound climate risks. Furthermore, Luhunga (2025) projected a rise in extreme rainfall frequency and intensity, particularly in coastal, central, and northeastern highland regions, accompanied by an increase in consecutive wet days and either stable or declining trends in consecutive dry days. These projections support the observed increase in WH events during extended wet seasons.

Figure 3 illustrates the interannual variability in the percentage of grid cells across Tanzania affected by compound hot-wet and hot-dry events from 1981 to 2023. The results reveal substantial year-to-year fluctuations in the spatial extent of both event types, with hot-dry events generally affecting a larger portion of the country than hot-wet events. However, the dominance of each type varies seasonally: hot-dry events tend to be more extensive during OND, while hot-wet events prevail during MAM. During MAM, hot-wet events affected more than 40% of the country, notably in 1988, 2002, 2003, 2010, and 2019. The

most widespread hot-dry extremes occurred during OND in 1987, 2005, 2010, 2016, and 2023. In the JF season, compound extremes appeared sporadically, with widespread hot-dry (hot-wet) events covering over 50% of Tanzania in 1999 and 2003 (1998 and 2016). These occurrences coincided with strong ENSO anomalies, highlighting the role of large-scale climate drivers during this transitional period. In contrast, the JJAS season shows a clear upward trend in the spatial extent and frequency of hot-wet events in recent decades, particularly after the early 2000s, with several years (2001, 2011, 2017, 2020, 2022, 2023) exceeding 50% spatial coverage. This indicates a possible shift toward warmer and wetter conditions during the main dry season, likely linked to regional warming and enhanced moisture transport from the Indian Ocean.

Overall, the observed spatial and seasonal contrasts suggest that both large-scale teleconnections and localized processes modulate the occurrence of compound extremes. Previous studies have highlighted the influence of SST anomalies: particularly those associated with ENSO, IOD, and western Indian Ocean warming on East African rainfall and temperature variability (Nicholson 2017; Dunning et al. 2018). The evident seasonal asymmetry in hot-wet and hot-dry events thus supports the hypothesis that SST-driven teleconnections influence the compound nature of these extremes by altering regional moisture transport, convection patterns, and surface energy balances.

3.2 Spatiotemporal Changes in occurrence and Spatial Extent of Compound Hot-Dry and Hot-Wet Events

Figure 4 shows the spatiotemporal heterogeneity and temporal intensification of compound hot-wet and hot-dry extremes across Tanzania for the successive decades spanning 1981–2023. This decadal evolution, analyzed during the extended warm season (October–May), aligns with recent evidence of increasing climate extremes across East Africa, driven by rising surface temperatures and shifting precipitation patterns (Ayugi et al. 2024; Gebrechorkos et al. 2023; Luhunga 2022; Muheki et al. 2024).

The southern coastal zone emerged as a persistent hotspot for hot-wet events, with frequencies consistently exceeding 10% of months in the most recent 2011–2023 period. This intensified wet–heat stress is highly attributable to enhanced ocean–atmosphere coupling processes, specifically the effects of positive IOD phases and continually warming SSTs which collectively modulate convective rainfall and moisture transport over Tanzania (Black et al. 2003; Manatsa et al. 2011). The observed shift from lighter to deeper red shading in the hot-wet panels directly suggests a strengthening of rainfall intensity, a phenomenon consistent with Clausius–Clapeyron scaling where warmer air masses hold and subsequently release more moisture, amplifying rainfall intensity. Conversely, the co-occurrence of hot-dry events remains low (< 5%), indicating a robust, sustained moisture availability, likely supported by reliable monsoonal inflows and strong sea-breeze circulations.

On the contrary, the northern coastal zone exhibits a dominance of elevated hot-dry frequencies, surpassing the 10% threshold from the 1990s onward. This spatial difference reflects distinct regional hydroclimatic controls, aligning with observed drying trends over northeastern Tanzania and southern Kenya, which are attributed to a combination of reduced long rains (MAM) and accelerated

evapotranspiration under regional warming (Luhunga 2025; Limbu and Makula 2024). The strengthening of hot-dry events here reflects a self-reinforcing warming–drying feedback loop, where rising temperatures exacerbate surface water deficits, thereby suppressing the initiation of convective rainfall. These dynamics may be further reinforced by regional-scale atmospheric subsidence and weakened moisture convergence during the crucial long rains season.

A notable shift toward more hot-dry events was observed in the southwestern highlands (Mbeya, Njombe, Iringa) with the frequencies approaching 10% of the months during 2011–2023. These regions, traditionally known for their cooler and wetter conditions, are now clearly exhibiting signs of progressive warming and rainfall reduction, consistent with current climate projections (Luhunga 2025; Chang’a et al. 2017). This shift may be driven by diminished moisture advection from the Congo Basin combined with enhanced subsidence linked to a strengthening subtropical high. These evolving hot-dry conditions pose a severe threat to rainfed agriculture (especially the production of staples like maize and beans) and introduce substantial risks to hydropower generation and overall water security, collectively compounding socio-economic vulnerabilities in these rural highland communities (Gebrechorkos et al. 2019).

Furthermore, the Lake Victoria Basin presents a hydro-climatically sensitive and complex pattern of compound extremes. The western basin recorded notably elevated hot-wet frequencies (> 13% of months during 2001–2010), a phenomenon likely driven by intense lake–land thermal contrasts that promote localized convection and moisture recycling (Anyah and Semazzi 2007; Thiery et al. 2016). Conversely, the southern basin has shown a transition toward hot-dry dominance in the last decade, signifying a shift to dry-heat stress due to reduced moisture inflow and elevated evaporation under rising temperatures, which aligns with projections of localized climate risks (Luhunga 2024).

The results across the seasons (appendices 1, 2, 3) reveals that this overall trend is composed of distinct, driver-specific seasonal regimes. The results for OND, show a progressive expansion of hot-wet extremes across the northern coastal zone and the Lake Victoria Basin in the latest decades. This intensification, with frequencies consistently exceeding 10% in the 2001–2010 and 2011–2023 periods, is primarily modulated by interannual climate modes, notably the IOD and the ENSO (Nicholson 2017; Rowell et al. 2015). The coincidence of a positive IOD phase and El Niño events is known to significantly amplify moisture convergence and rainfall anomalies across the equatorial East African coast (Rohli et al. 2019; Saji et al. 1999), leading to the observed hot-wet surges. The JF analysis reveals a distinct regional divide, with the Lake Victoria Basin showing consistently high hot-wet frequencies (> 13% in the western basin) due to dominant localized convection driven by strong lake–land thermal contrasts (Anyah & Semazzi, 2007; Thiery et al., 2016). In contrast, the northern interior and central zones show an emergence of hot-dry extremes during this period of high insolation and reduced large-scale rainfall, which highlights the growing threat of high-temperature induced water stress even outside the main dry season. A progressive intensification and widening area of hot-dry extremes was observed during MAM, with frequencies stabilizing around the 10% threshold in the latest decade. This finding is deeply concerning, as it reflects the widely documented failure or weakening of the long rains over northeastern

East Africa (Funk et al., 2018; Luhunga, 2025), exacerbated by concurrent high temperatures that create the severe warming–drying feedback loop (Limbu and Makula 2024). Conversely, the unimodal southern and southwestern regions continue to exhibit high hot-wet frequency during MAM, consistent with an increase in extreme wet days driven by enhanced moisture flux convergence from the Indian Ocean (Chang’a et al. 2017; Luhunga 2024).

Figure 4 depicts the spatial distribution and decadal intensification of hot-wet and hot-dry compound extremes across Tanzania during the JJAS season. This analysis reveals a pronounced spatial contrast and a clear temporal intensification, aligning with the broader regional warming and hydroclimatic shifts discussed previously. During the earlier decades (1981–2000) in Fig. 4a–d, hot-wet events (8–16% monthly frequency) were concentrated over the southwestern highlands and the western interior. This distribution suggests that occasional moisture surpluses coincided with warm anomalies, likely facilitated by episodic incursions of moist Congo air masses and enhanced zonal moisture advection from the west. In parallel, hot-dry events during this period were more localized, primarily confined to central Tanzania (Fig. 4b, 4d), indicating an occasional co-occurrence of dry and warm conditions in this semi-arid core.

A notable spatial reorganization and intensification emerged after 2001. The hot-wet frequencies expand markedly toward the northwestern and northern sectors (Fig. 4e, 4g), particularly across the Lake Victoria basin and northeastern highlands. In the 2011–2023 period, hot-wet frequency in these northern regions substantially exceeds 20% of months, marking a significant escalation of compound hot-wet extremes in regions that climatologically experience modest JJAS rainfall. This enhancement is likely attributable to stronger regional warming coupled with lake-induced convection and enhanced atmospheric moisture linked to warming lake surfaces (Thiery et al. 2016; Anyah and Semazzi 2007). Furthermore, this increase coincides with changes in atmospheric circulation, such as the intensification of the tropical easterly jet and shifts in the Walker circulation, which favor convective uplift over northern Tanzania (Nicholson 2017; Zhao and Cook 2021).

In contrast, hot-wet events (Fig. 4b, 4d, 4f, 4h) exhibit a more confined but persistently strengthening pattern centered over the central and southern interior regions, notably around Dodoma, Singida, and parts of Iringa. Frequencies reached 16–20% in localized areas during the 2011–2023 period, underscoring the growing vulnerability of these semi-arid zones to compound heat–dryness stress. This finding is consistent with projections by Luhunga (2025) and Gebrechorkos et al. (2019), who report intensified warming and a decline in seasonal rainfall over the central plateau and southern highlands. The persistence of hot-dry extremes in these regions highlights the acute sensitivity of rainfed agricultural systems and semi-arid ecosystems to concurrent temperature and moisture deficits.

A shift was also observed in the southwestern highlands, which were hot-wet hotspots in earlier decades but now show a reduction in hot-wet and a modest tendency toward hot-dry dominance in the most recent period. This may reflect reduced moisture influx from the Congo Basin and enhanced regional subsidence, consistent with broader drying trends documented across southern Tanzania (Chang’a et al.

2017; Lyon 2014). Such transitions carry substantial implications for crop productivity, rangeland conditions, and hydropower reliability, as these highlands are critical to both agricultural output and river flow regulation. In essence, the JJAS season establishes a clear north–south dichotomy in compound extremes: increasing hot-wet in the northern regions linked to moisture enhancement, and strengthening hot-dry in the central/southern interior reflecting accelerated warming–drying interactions. The progressive darkening of shades in both hot-wet and hot-dry panels across decades definitively illustrates the temporal intensification of compound extremes over Tanzania, reflecting the amplified, spatially dependent risks.

To further elucidate the evolving dynamics of compound extremes across Tanzania, we conducted spatial trend analyses using the non-parametric Mann–Kendall test and Sen’s slope estimator for the 1981–2023 period (Fig. 6 and Table 1). These analyses reveal pronounced spatial and seasonal contrasts, highlighting regions most vulnerable to changing climatic conditions. Overall, the results show a statistically significant ($p < 0.01$) increasing trend in hot-wet events across most of Tanzania, particularly during the extended warm season (October–May). This widespread positive trend in WH frequency is consistent with the observed regional warming and the concurrent intensification of humidity levels over East Africa during the past four decades (Gebrechorkos et al. 2019; Nicholson 2017). In contrast, hot-dry events display more localized and less coherent spatial patterns, with statistically significant trends largely confined to limited areas.

The seasonal breakdown reveals distinct patterns. During the JF period, the increase in hot-wet event frequency is most pronounced over the southern coast, northeastern highlands, and eastern Lake Victoria basin, with Sen’s slope values exceeding 0.002 events per decade. This pattern is consistent with reported global increases in compound hot–wet extremes under intensified greenhouse forcing (Dong et al. 2025; Wu et al. 2019). However, a significant decreasing trend in WH events is evident across parts of northeastern Tanzania during JF, reaching magnitudes of up to -0.6 events per decade (Fig. 6a). This localized decline in hot-wet extremes supports the earlier frequency distributions (Fig. 2). Conversely, hot-dry events during JF show an increasing trend over northwestern Tanzania, while localized decreases appear in the southern highlands (Fig. 6b). These divergent regional signals may reflect interannual moisture variability associated with the ITCZ’s position and strength, as well as local land–atmosphere feedbacks influencing surface energy partitioning.

The MAM season exhibits predominantly weak or neutral trends in both hot-wet and hot-dry events (Fig. 6c, 6d), consistent with the season’s high rainfall and buffered temperature variability. This general stability suggests that MAM remains a climatologically balanced season, where abundant rainfall tends to suppress the co-occurrence of hot–dry events and buffer heat extremes. In the OND short rains, a significant and widespread increasing trend in hot-wet events is observed across southern, northern coastal, and northeastern highland regions (Fig. 6e). The numerous statistically significant positive Sen’s slopes indicate a robust increase in hot-wet extremes during this season that historically registered the lowest hot-wet frequency (Fig. 4). This shift is noteworthy, as it likely reflects warming-induced changes in the short rains regime, including altered Sea Surface Temperature (SST) patterns in the western Indian

Ocean (Lyon and DeWitt 2012; Zhao and Cook 2021). The hot-dry events during OND show weaker and more spatially patchy patterns, with declining trends over the southern regions, suggesting the climate system is favoring humid–heat over dry–heat extremes during this transitional season.

Table 1
Mann-Kendall trend analysis of seasonal compound hot-wet and hot-dry events
area coverage across Tanzania from 1981 to 2023

Hot-wet				Hot-dry		
Season	Trend	Slope	p-value	Trend	Slope	p-value
JF	increasing	0.0006	0.0344	no trend	0.0002	0.1695
MAM	no trend	0.0006	0.3356	no trend	0.0004	0.1310
OND	increasing	0.0012	0.0000	increasing	0.0028	0.0004
Oct-May	increasing	0.0011	0.0000	increasing	0.0010	0.0113
JJAS	increasing	0.0025	0.0000	no trend	-0.0000	0.9416

During the JJAS dry season, hot-wet events also exhibit a significant increasing trend across much of Tanzania (Fig. 6i), with spatial maxima in the northern and coastal regions. These results strongly reinforce the decadal frequency patterns shown in Fig. 5, confirming a systematic shift toward more frequent hot-wet conditions even during the climatologically driest months. In contrast, DH events during JJAS display no significant trend (Fig. 6j), suggesting that the dominance of dry–hot extremes have either plateaued or weakened over time.

The spatiotemporal assessment indicates a clear asymmetry in the evolution of compound extremes in Tanzania. Hot–wet events exhibit a consistent intensification and geographic expansion, while hot–dry events are largely confined to specific regions or display decreasing tendencies over time. Nationally averaged, hot-wet events show a statistically significant upward trend (p-value; 0.0344), whereas hot-dry events show no significant trend (Table 1). These observed trends align with broader East African warming patterns, enhanced regional moisture convergence, and land–surface feedbacks under anthropogenic climate forcing (Seneviratne et al., 2021; Raymond et al., 2020). The consistency between the long-term trend analysis (Fig. 6) and the decadal evolution (Fig. 4 and Fig. 5) reinforces the robustness of the detected climate signal, confirming that the changes are part of a sustained climatic transition toward a warming and moistening trajectory across much of Tanzania. The resulting dominance of hot-wet extremes and the localized persistence of hot-dry extremes hold significant implications for agriculture, public health, and water resources, underscoring the urgency of strengthening seasonal early warning systems and climate-resilient planning, particularly in the emerging critical windows of vulnerability during the JF and OND seasons (Luhunga 2022, 2025).

3.3. Influence of large-scale drivers on Compound Hot-Wet and Hot-Dry Extremes

We examined the influence of large-scale oceanic drivers on the occurrence of compound hot-wet and hot-dry events over Tanzania using composite difference analysis (Fig. 7, 10, 11) and quantification via Pearson correlation with climate indices (Fig. 8, 12, 13). The composite difference analysis revealed that hot-wet extremes are associated with pronounced warming over the central and eastern equatorial Pacific, the western Indian Ocean, and the tropical Atlantic (Fig. 7a, b, c, d). This pattern, consistent with El Niño-like SST conditions, is known to weaken the Pacific Walker circulation, enhance eastward convection, and promote moisture flux convergence over East Africa (Rwambo et al. 2025; Ongito and Limbu 2024). Concurrent warming over the western Indian Ocean further strengthens the westerly moisture inflow toward the Tanzanian coast, reinforcing simultaneous heat and rainfall anomalies. In contrast, hot-dry events exhibit cooling in the same Pacific regions, consistent with La Niña conditions that strengthen the Walker circulation, leading to enhanced subsidence and suppressed convection and rainfall over East Africa. Additional SST anomalies over the southeastern Indian Ocean (EA; 16°–30°S, 165°E–155°W) and the southern Atlantic (SA; 37°–54°S, 20°–49°W) suggest secondary regional influences on atmospheric stability and moisture transport, particularly during the OND season. These regions have been specifically linked to suppressed rainfall over Tanzania under warmer SST conditions (Makula and Zhou, 2022). Overall, the composite structures highlight the dominant roles of the Pacific and Indian Oceans in shaping the spatiotemporal variability of compound extremes across Tanzania.

Pearson correlation analyses confirmed these physical links. For hot-wet extremes, significant positive correlations ($0.45 < r < 0.6$) emerge over the western Indian Ocean, central and eastern equatorial Pacific, and parts of the tropical Atlantic (Fig. 8, not shown here), indicating the combined effects of El Niño and positive IOD phases in enhancing hot-wet event occurrences. Conversely, hot-dry extremes show negative correlations over the same regions, consistent with La Niña-like SST structures that suppress convection. The observed secondary positive SST anomaly over the East of Australia during hot-dry events further supports earlier findings by Makula and Zhou (2022), linking warmer SSTs in this region with suppressed precipitation over Tanzania.

Further analysis of the seasonal frequencies of hot-wet and hot-dry events with the concurrent and preceding Niño3.4 and DMI indices (Fig. 9) revealed strong season-dependent and lagged relationships, which are critical for operational forecasting. The hot-wet events exhibited statistically significant positive correlations with concurrent Niño3.4 ($r = 0.63$) and DMI ($r = 0.44$) during the JF season. The associations were strengthened by lagged SST forcing from the preceding OND season, where Niño3.4 and DMI values correlated strongly with hot-wet occurrences in JF ($r = 0.67$ and $r = 0.55$, respectively). This lagged relationship reflects the persistence of oceanic anomalies and the delayed atmospheric response associated with ENSO evolution. DMI also showed significant correlations with hot-wet events during OND ($r = 0.42$) and JJAS ($r = 0.43$), suggesting that IOD variability exerts a sustained influence beyond its climatological peak in boreal autumn. Conversely, hot-dry extremes showed a significant negative correlation with concurrent Niño3.4 during JJAS ($r = -0.43$), consistent with La Niña conditions. Weak negative correlations of hot dry with DMI during OND and JF suggest that negative IOD phases reinforce drought conditions.

Both individual ENSO (Fig. 10, 12) and positive IOD (Fig. 11, 13) phases are associated with widespread positive composite anomalies and correlations for hot-wet events. The IOD influence, particularly during the OND season, often shows a wider spatial coverage, reflecting its proximity and direct influence on regional moisture transport. Conversely, the opposite phases show widespread negative anomalies and correlations for hot-dry events. The influence of ENSO on hot-dry events exhibits notable spatial heterogeneity during the MAM and JJAS seasons. During the positive phase, an increased frequency of hot-dry events is observed along the coastal regions, the northeastern highlands, and around the Lake Victoria Basin. Conversely, the negative phase is associated with more frequent hot-dry events over the northwestern parts of the region during MAM and across portions of the southwestern highlands during the JJAS season.

The analysis of combined ENSO and IOD phases (Fig. 14–15) revealed a profound synergistic effect where the co-occurrence of the same-sign phases maximizes the spatial extent and intensity of the compound extremes. The composites for the combined El Niño and Positive IOD phases (Fig. 14a, b, d) showed maximal and most widespread positive anomalies across all seasons compared to the individual drivers. Correspondingly, the spatial correlations (Fig. 15a, b, d) were larger and stronger, confirming that this coupled state provides the optimal condition for WH extremes. Similarly, the combined La Niña and Negative IOD phases yielded the most extensive negative anomalies and correlations (Figs. 14 and 15, Bottom rows), verifying that the synchronized influence of these opposing phases maximally suppresses convection and reinforces the likelihood of hot-dry extremes across the country.

The results decisively establish the dominant and synergistic roles of the tropical Indo-Pacific SST variability via ENSO and IOD in modulating compound hot-wet and hot-dry extremes over Tanzania. The findings are strongly consistent with previous studies that demonstrated the combined modulation of East African rainfall extremes by ENSO and IOD during OND (Black et al. 2003; Nicholson 2015; Wainwright et al. 2021). The mechanism for hot-wet extremes involves El Niño weakening the Walker circulation and promoting eastward convection, a process significantly amplified by the positive IOD's warm western pole, which injects reinforced westerly moisture flux into East Africa.

For hot-dry extremes, the canonical La Niña strengthening of the Walker circulation causes increased subsidence and suppressed convection, a drought-favoring state reinforced by the lack of moisture advection during negative IOD phases. This coupled atmospheric-oceanic response, particularly the enhanced effects under same-sign phase co-occurrence, is the fundamental physical driver of compound hazards in the region. The strong seasonal dependence and the significant lagged correlations ($r > 0.6$) for hot-wet events with indices from the preceding season (OND to JF) hold immense practical importance. This memory in the SST system offers a multi-month lead time, providing a powerful diagnostic framework for integrating these metrics into seasonal forecasting and early warning systems. Improved forecasts distinguishing between high hot-wet risk (flood, waterborne disease) and high hot-dry risk (drought, heat stress) are crucial for optimizing preparedness measures

across Tanzania's vulnerable sectors, including agriculture, water resource management, and public health.

4. Summary and Conclusion

This study provides the first comprehensive spatiotemporal assessment of compound hot–wet and hot–dry extremes across Tanzania, revealing pronounced seasonal asymmetry, regional differentiation, and increasing frequency over the past four decades. The hot-wet events are highest in the central/south during MAM, while hot-dry events are highest in the north/west during OND. Both hot-wet and hot-dry events are intensifying significantly, particularly during the OND and the JJAS dry season, suggesting a rapidly increasing year-round climatic risk. hot-wet extremes dominate during the MAM and OND seasons, while hot-dry extremes prevail in OND and JJAS. Both types have intensified since 2011, reflecting a warming climate and heightened hydroclimatic variability. The results demonstrate that ENSO and IOD are the dominant large-scale modulators of these compound events, with same-phase combinations (El Niño + positive IOD; La Niña + negative IOD) exerting the strongest synergistic influence. The detection of lagged relationships between OND SST anomalies and JF compound events highlights a promising window for predictive early warning of compound hazards in Tanzania.

By linking local-scale extreme patterns with global oceanic drivers, this work extends previous East African analyses (Nicholson 2017; Dunning et al. 2018; Ayugi et al. 2024) to the compound domain and situates Tanzania within the broader global context of increasing concurrent temperature–precipitation extremes (Hao et al. 2018; Dong et al. 2025). The emerging trends underscore the urgency of integrating compound-event risk metrics into national adaptation plans and seasonal climate forecasts. Tanzania's growing exposure to both hot–wet and hot–dry extremes underscore the necessity for climate-resilient strategies in agriculture, water management, and public health. The mechanistic insights provided here, particularly regarding the synergistic ENSO–IOD influence and its lagged predictability, offer a foundation for developing region-specific S2S early-warning systems and enhancing preparedness for compound climate hazards across East Africa.

Declarations

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Declaration of Competing Interest

The authors declare no conflict of interest.

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Data Availability

The temperature and precipitation datasets used in this study are freely available at https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.09/cruts.2503051245.v4.09/. The sea surface temperature data used in this study were obtained from the Japanese Meteorological Agency (JMA), which is also freely available at <https://psl.noaa.gov/data/gridded/data.cobe.html>. The Nino 3.4 and DMI indices used in this study are also freely available at <https://psl.noaa.gov/data/timeseries/monthly/NINO34/> and <https://psl.noaa.gov/data/timeseries/month/DMI/>, respectively. The code used for the analysis and visualization is available from the corresponding upon a reasonable request.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Wilfred Paulo Kessy. The first draft of the manuscript was written by Exavery K. Makula and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript

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Figures

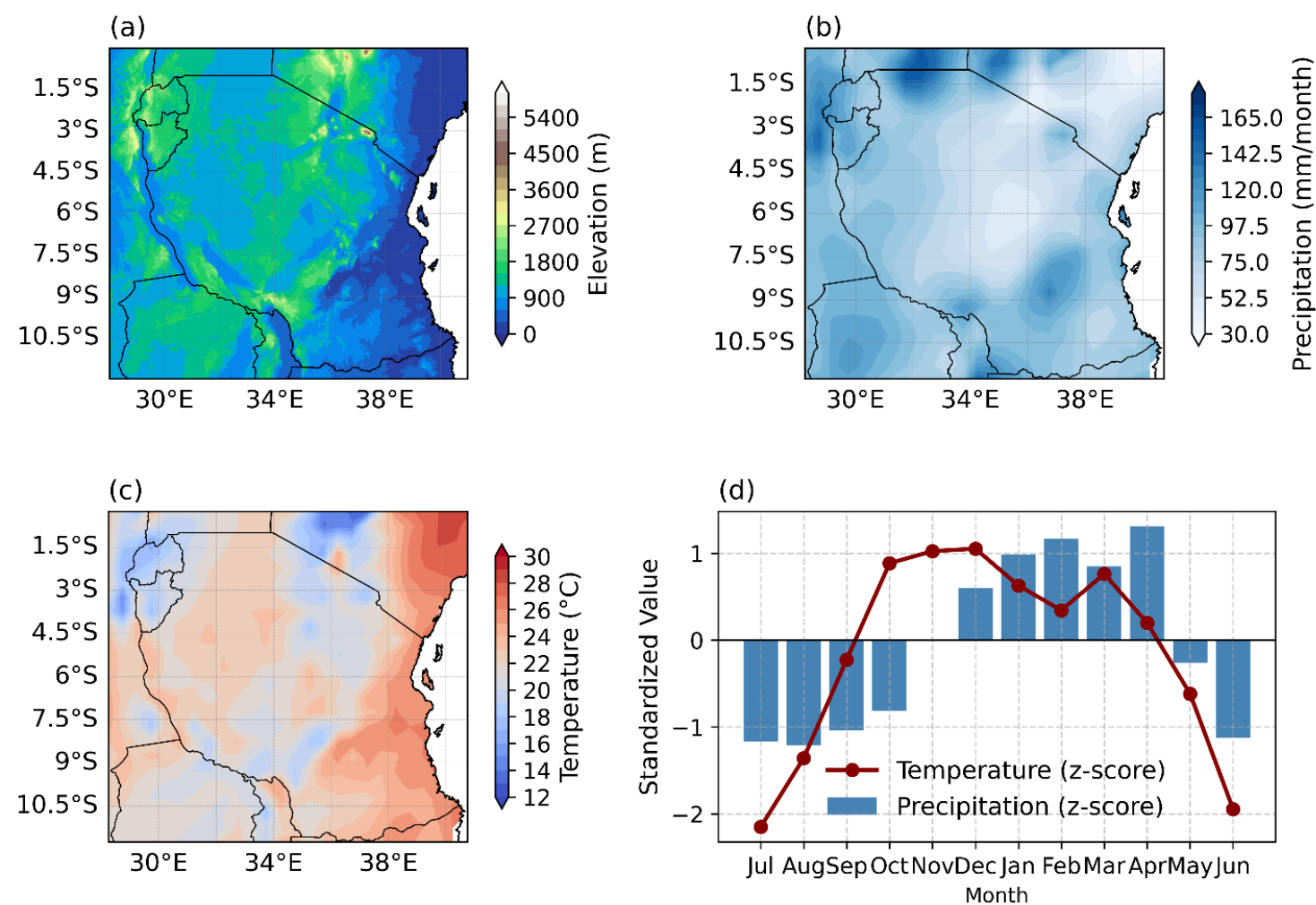


Figure 1

Geographic and climatic characteristics of the study area (Tanzania). (a) Elevation, (b) Mean annual precipitation (mm month⁻¹; 1981–2023), and (c) Mean annual near-surface air temperature (°C; 1981–2023). (d) Standardized anomalies of area-averaged precipitation (bars) and temperature (line) for Tanzania (1981–2023).

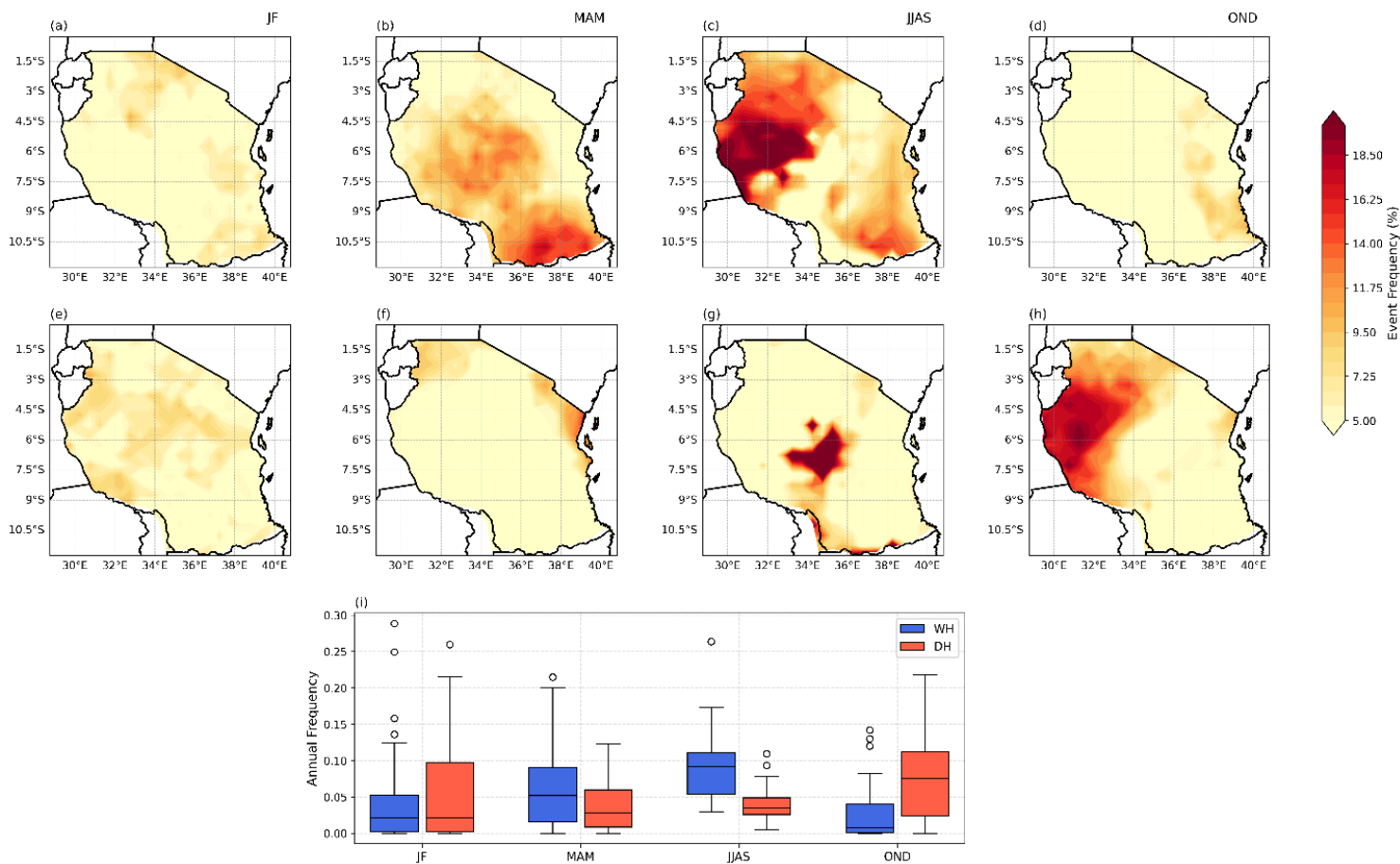


Figure 2

Spatial distribution and seasonal occurrence of compound hot–wet (first row) and hot–dry (second row) events over Tanzania during 1981–2023. The maps show the percentage frequency of events in each grid cell for the JF (a & e), MAM (b & f), JJAS (c & g), and OND (d & h) seasons, while the boxplots summarize the average events count for each season.

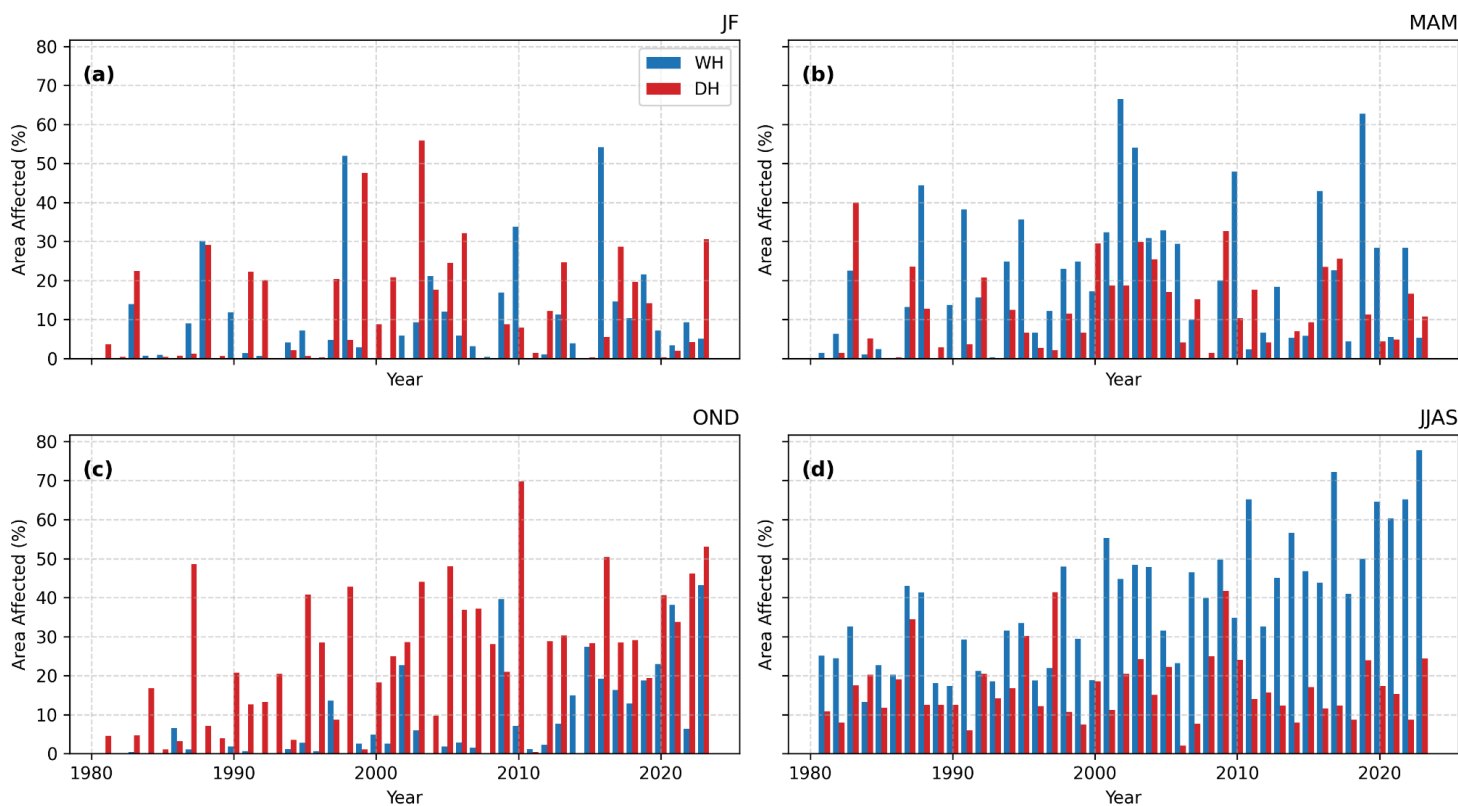


Figure 3

Annual percentage of area affected by compound events across four seasonal periods over Tanzania from 1981 to 2023. Panels show the spatial extent of grid cells experiencing hot-wet (blue bars) and hot-dry (red bars) extremes during (a) JF, (b) MAM, (c) OND, and (d) JJAS.

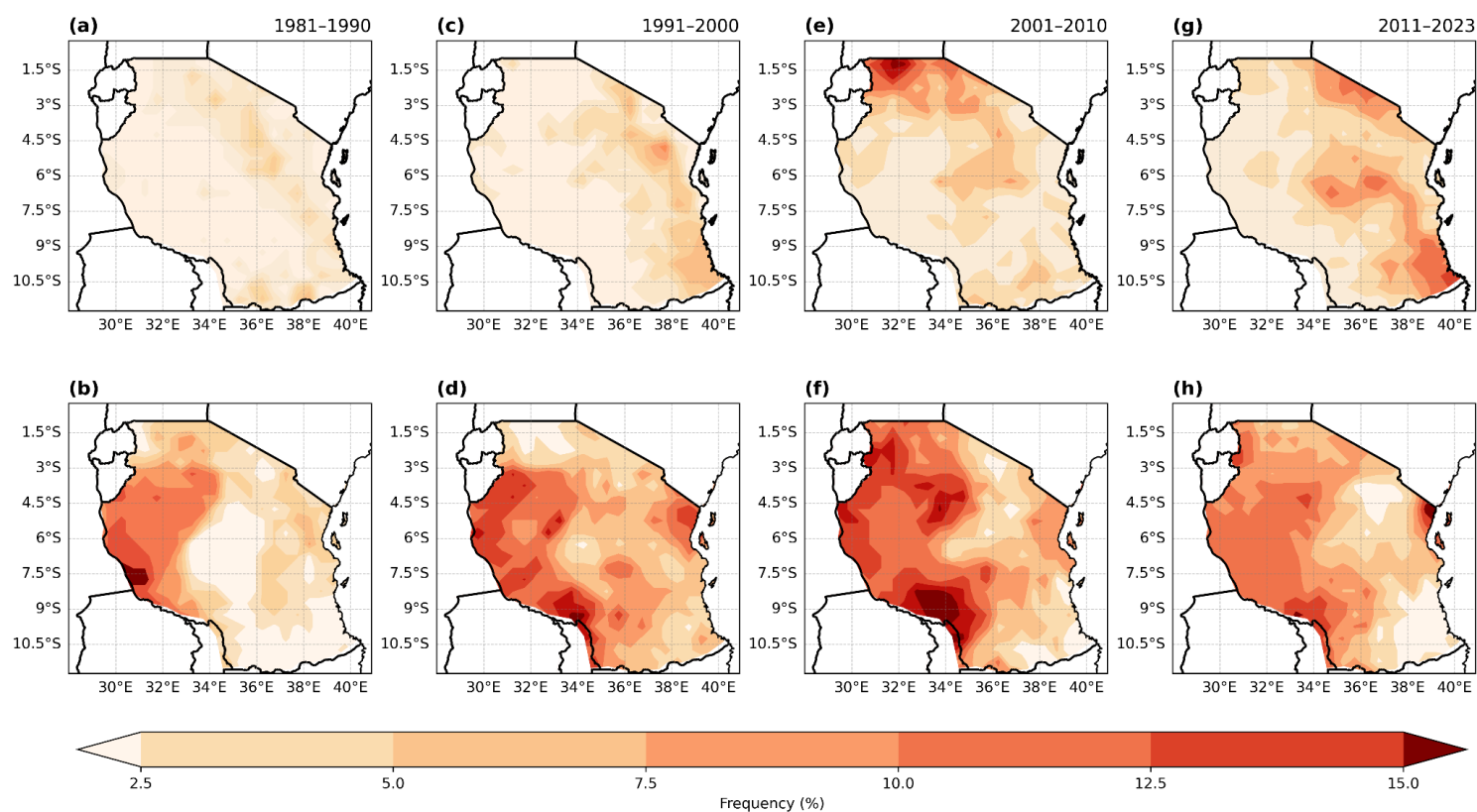


Figure 4

Spatial distribution of the frequency (%) of compound hot-wet events (top row) and hot-dry events (bottom row) over Tanzania during the October to May season for successive decades within the period 1981–2023.

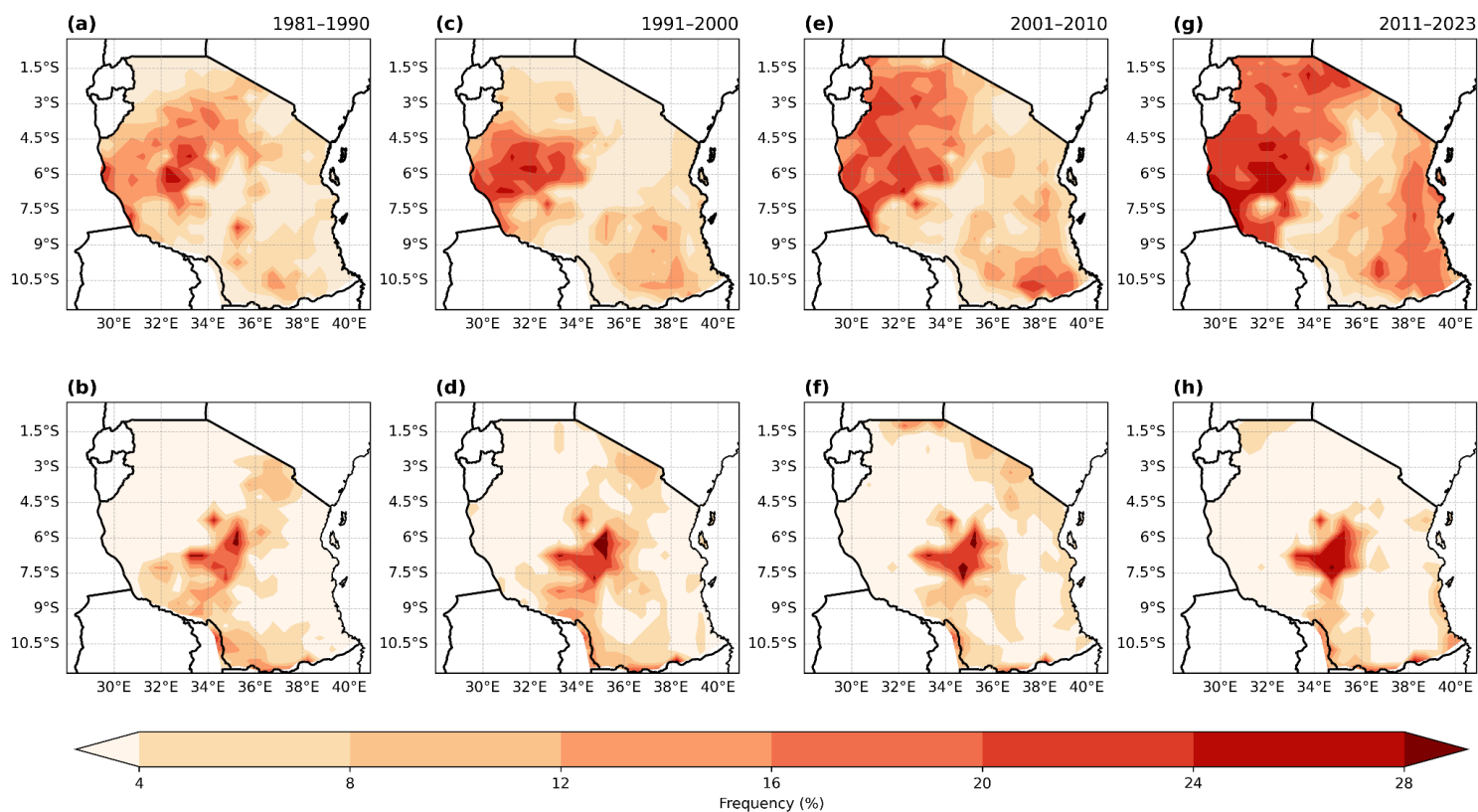


Figure 5

Same as Fig. 4 for JJAS season

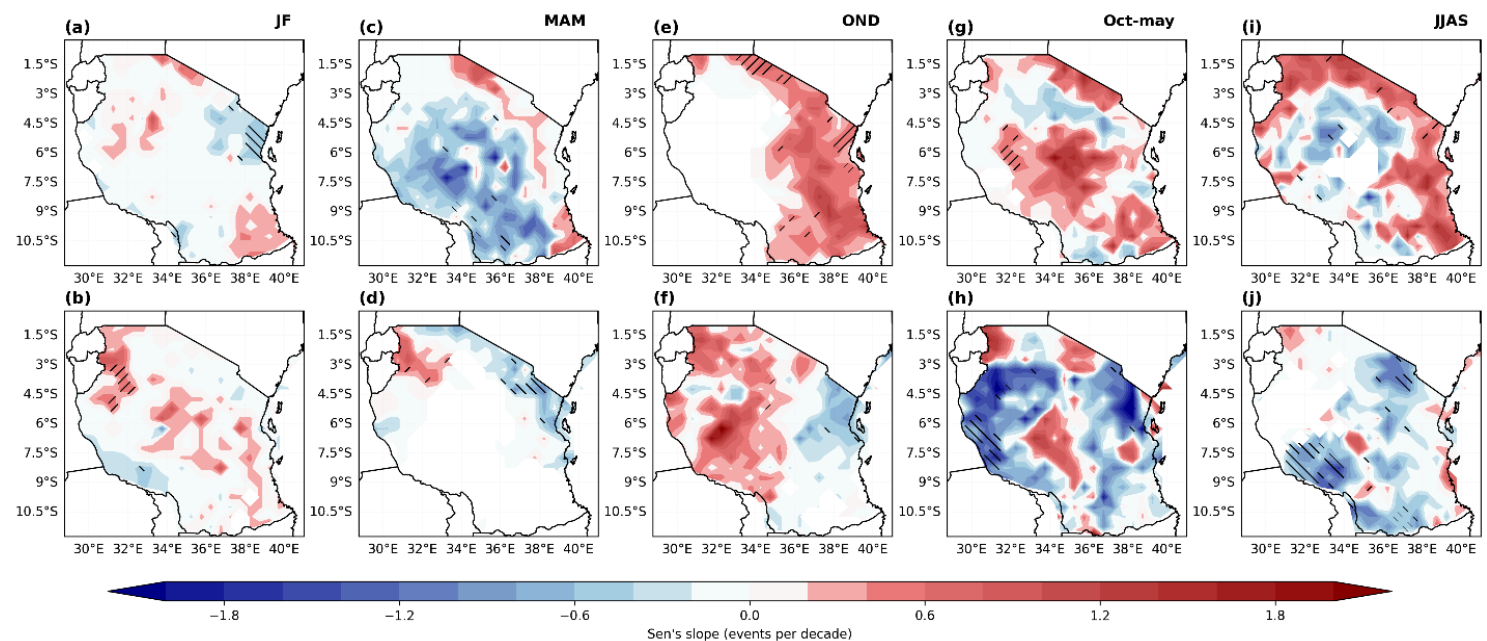


Figure 6

Spatial trends in the frequency of compound hot-wet (top row) and dry-hot (bottom row) events over Tanzania for the JF, MAM, OND and JJAS seasons during 1981–2023. Statistically significant trends ($p < 0.05$) are indicated by hatching on the maps.

0.1) from the Mann–Kendall test are highlighted, with forward slash hatching indicating increasing trends and back slash hatching indicating decreasing trends.

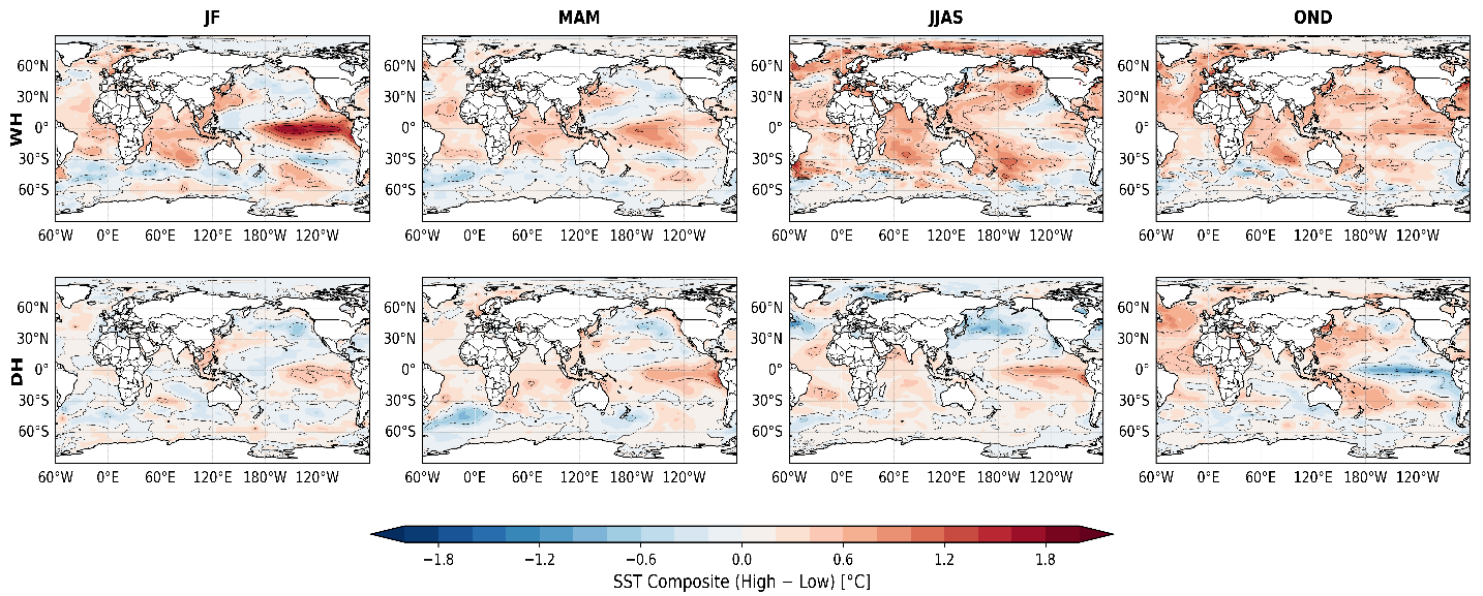


Figure 7

Composite differences of SST anomalies between months with high and low frequencies of compound hot–wet (top row) and hot–dry (bottom row) events over Tanzania for the (a,e) JF, (b,f) MAM, (c,g) JJAS, and (d,h) OND seasons during 1981–2023.

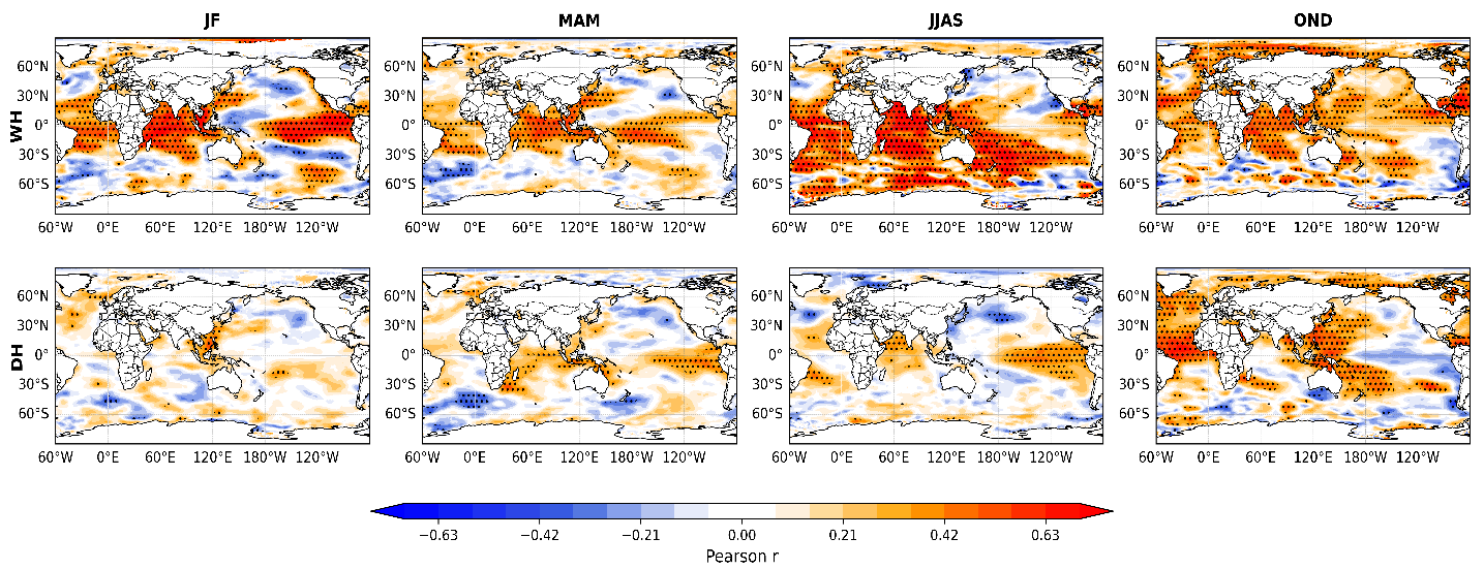


Figure 8

Spatial distribution of Pearson correlation coefficients between monthly sea surface temperature (SST) anomalies and the occurrence of compound hot–wet (top row) and hot–dry (bottom row) events over

Tanzania for the (a & e) JF, (b & f) MAM, (c & g) JJAS, and (d & h) OND seasons during 1981–2023. Black dots indicate statistically significant correlations at the 95% confidence level.

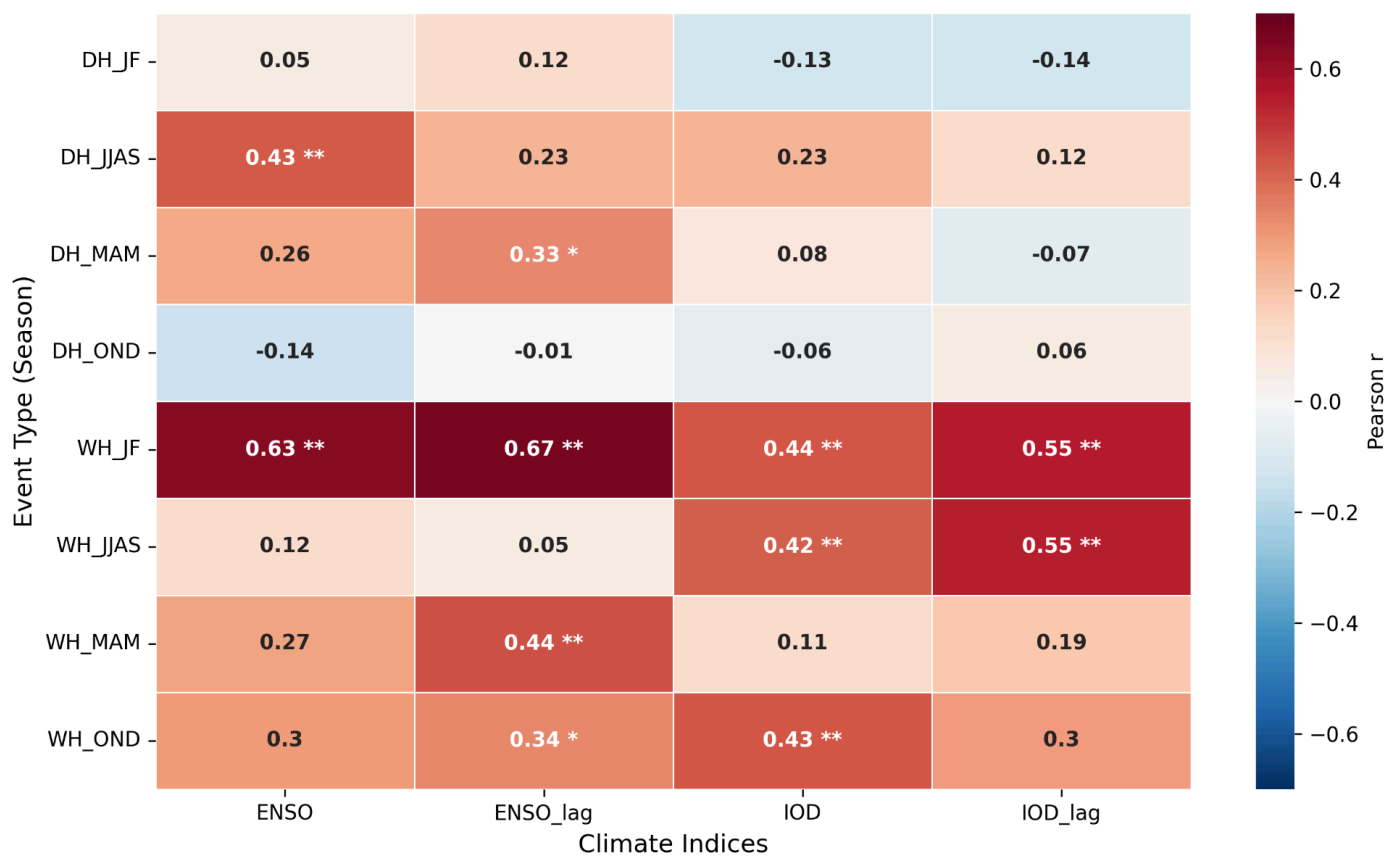


Figure 9

Heatmap of Pearson correlation coefficients (r) between hot-wet and hot-dry events over Tanzania and climate indices (ENSO: NINO3.4 index, IOD: DMI). Both concurrent-season and preceding-season (lag) correlations are shown. Significance levels are indicated as $p < 0.01$ (**) and $p < 0.05$ (*).

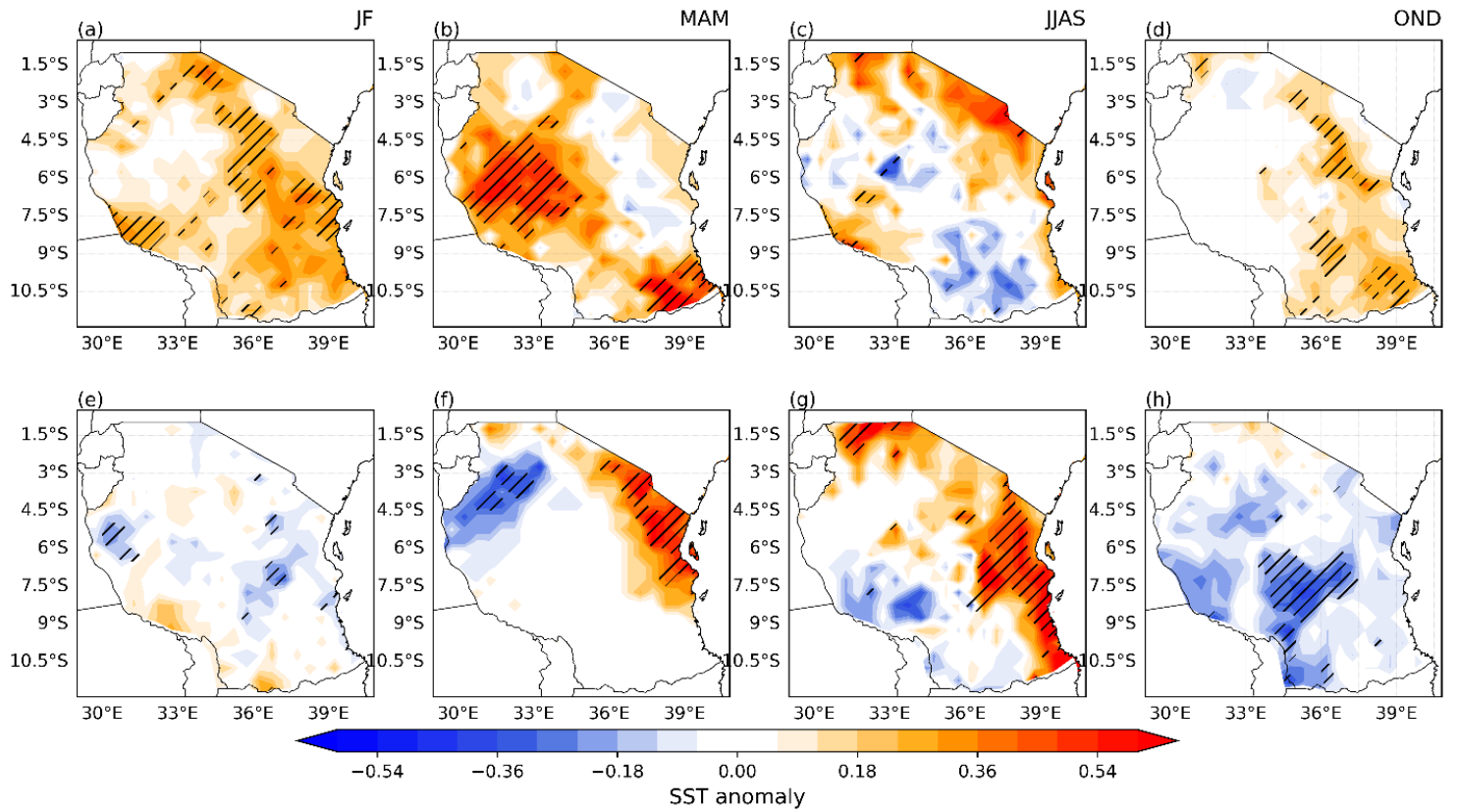


Figure 10

Composite Difference in compound extreme hot-wet (top row) and hot-dry (bottom row) Occurrence During ENSO Phases. Diagonal hatching shows the areas of significant differences at a confidence level of 90%.

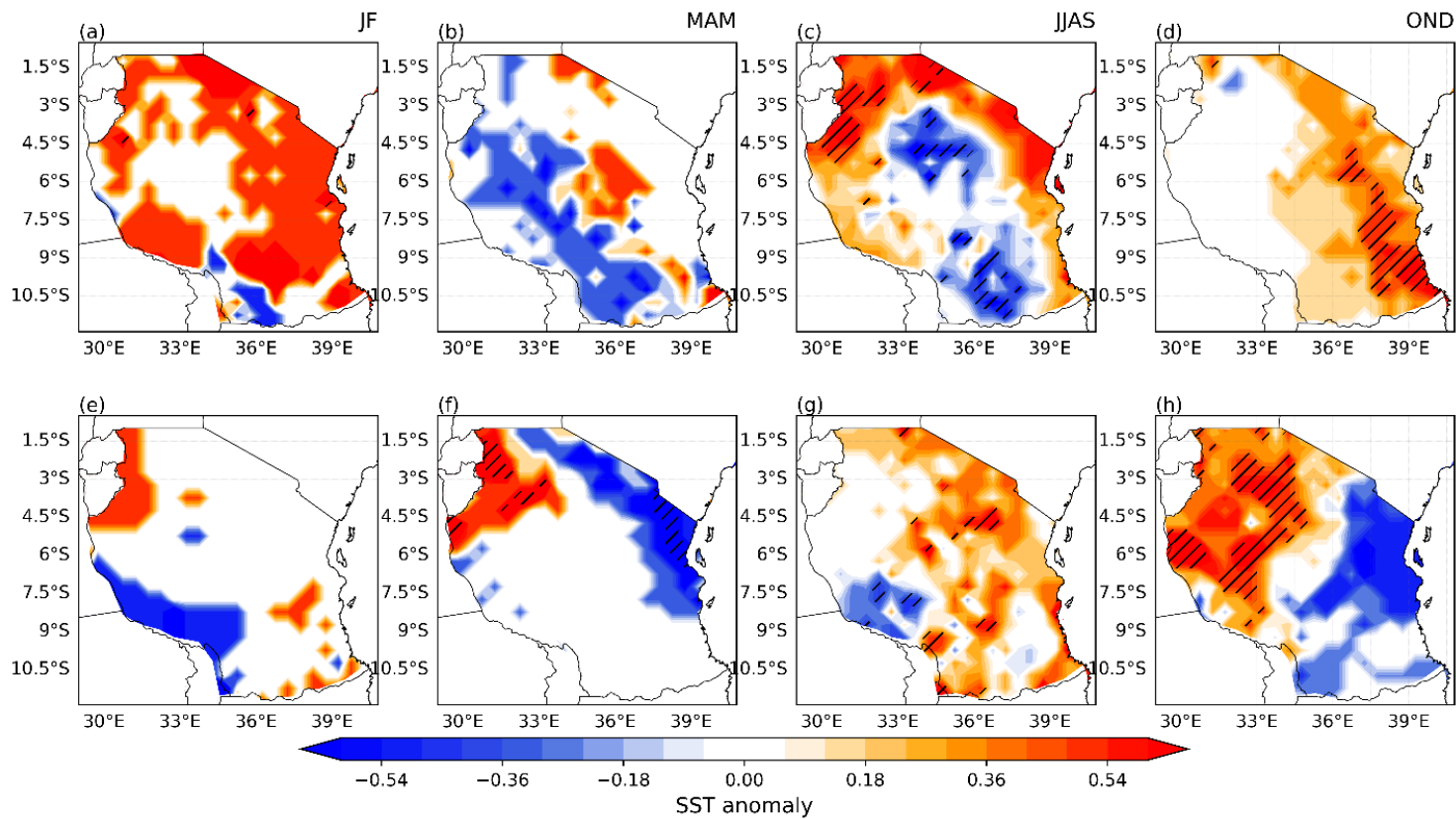


Figure 11

Similar to Fig 10. For IOD

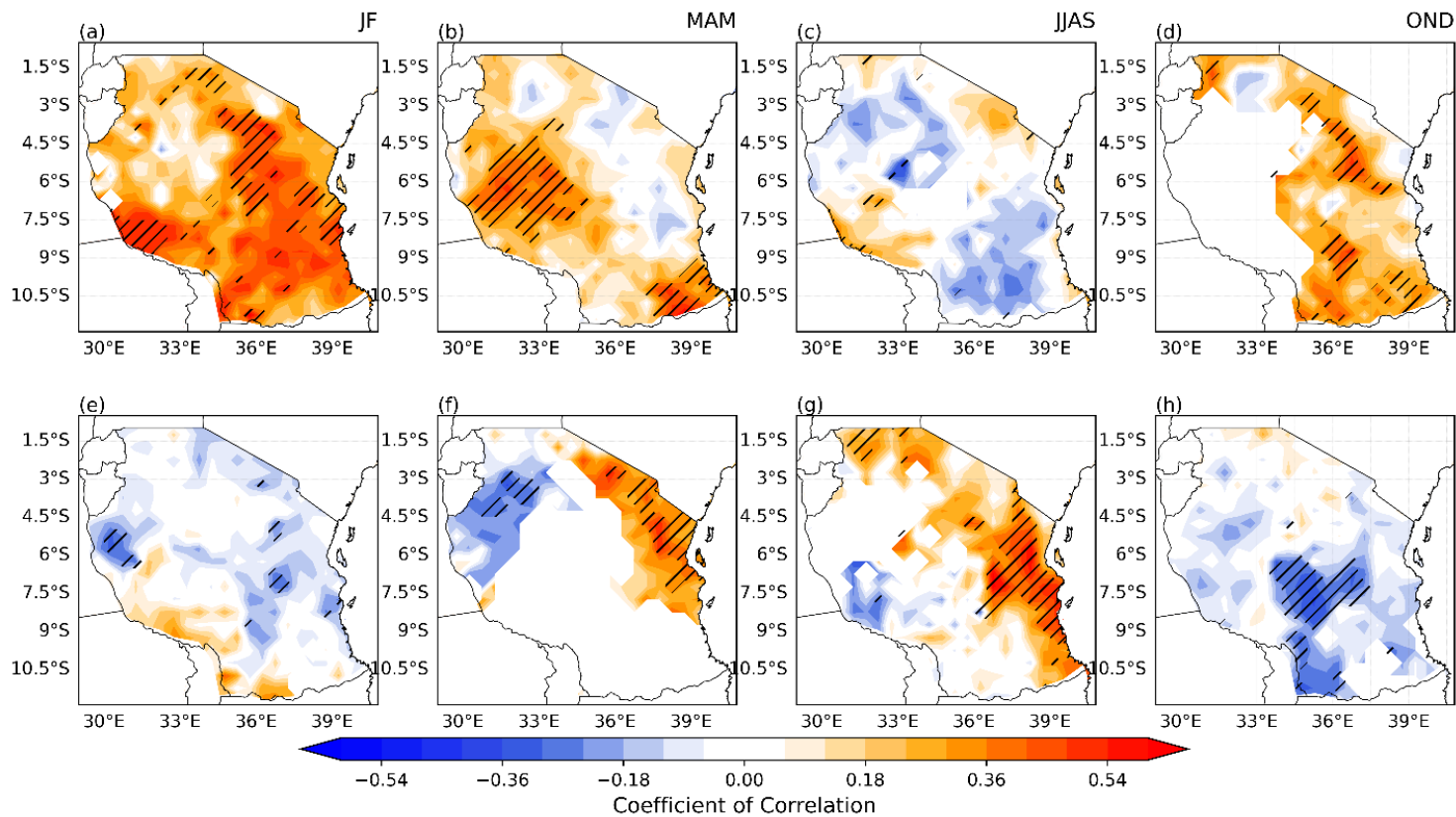


Figure 12

Spatial correlation between ENSO (Niño 3.4 index) with hot-wet (top row) and hot-dry (bottom row) over Tanzania during four seasonal periods: JF (a & e), MAM (b & f), JJAS (c & g), and OND (d & h), spanning 1981–2023. Diagonal hatching marks grid cells where correlations are statistically significant at the 90% confidence level.

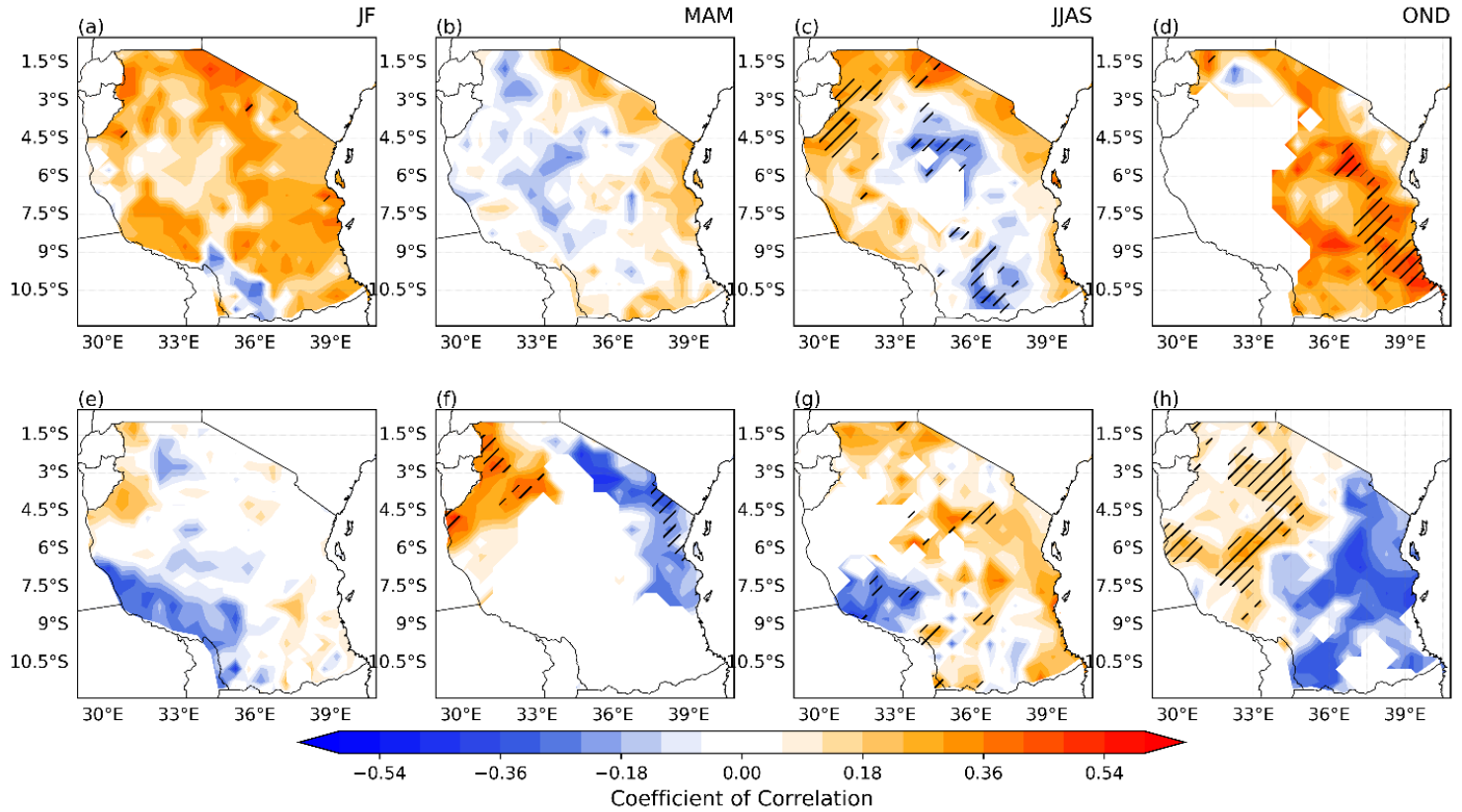


Figure 13

same as in **Fig 12**, but for the IOD (DMI index).

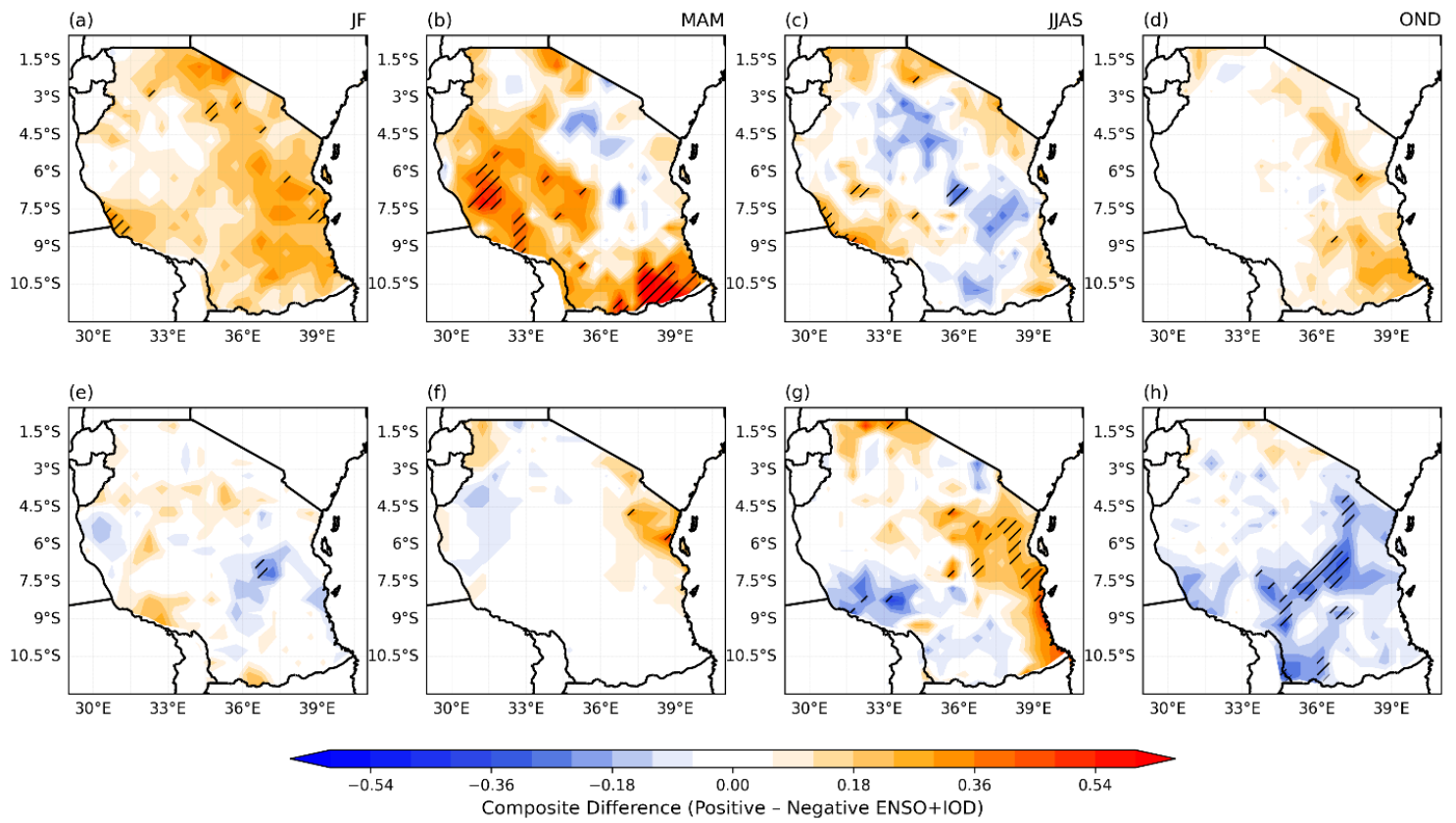


Figure 14

Composites difference in compound hot-wet (top row) and hot-dry (bottom row) occurrence during combined ENSO and IOD events.

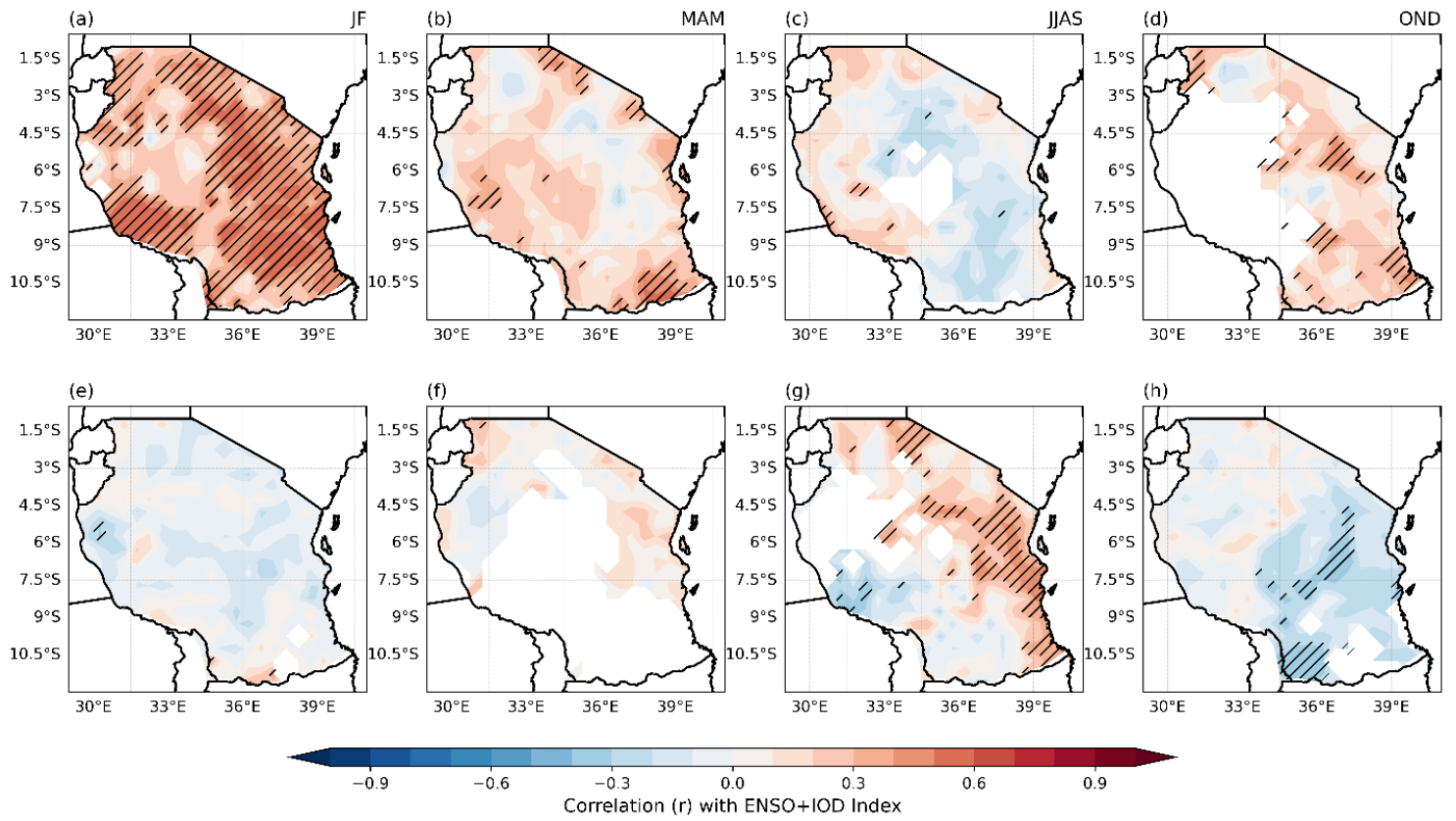


Figure 15

Correlation coefficients between occurrence of compound hot-wet (top row) and hot-dry (bottom row) extremes and combined ENSO-IOD indices.

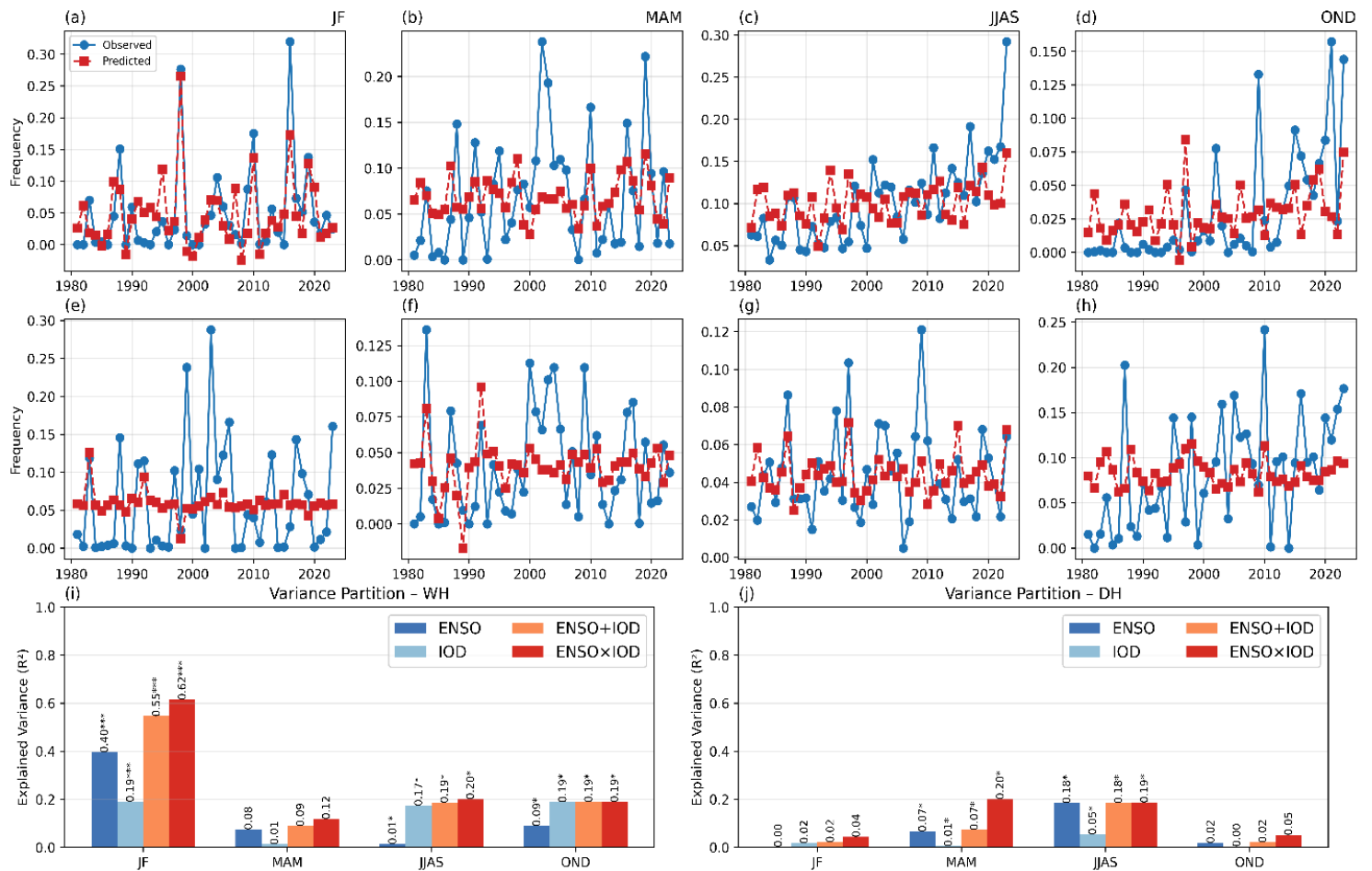


Figure 16

Observed (blue circles) and predicted (red squares) frequencies of hot-wet and hot-dry events in Tanzania for four seasons (JF, MAM, JJAS, OND) from 1981–2023. Panels a–d: hot-wet events; e–h: hot-dry events. Panels i–j: Variance partitioning (R^2) showing contributions from ENSO, IOD, their combined effect, and the ENSO×IOD interaction. Asterisks indicate model significance: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Supplementary Files

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- [SupplementaryFIGURES.docx](#)