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Inter-tropical African precipitation regime shifts dominated by tropical easterly jet

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Abstract

Since the 1990s, inter-tropical Africa (ITA) has experienced consecutive calamitous droughts during the boreal spring. Although the observed precipitation regime changes have been attributed to tropical Indian Ocean-western Pacific warming and/or tropical Pacific La Niña-like cooling, the model-projected past-to-future widespread wetting response to anthropogenic warming overshadows qualitative attributions of decadal shifts in historical precipitation regimes and the reliability of near-term projections. The causes of ITA precipitation regime shifts and the likelihood of their future continuation remain unclear. Here, we reveal that the observed monopolar precipitation changes in ITA are primarily driven by the tropical easterly jet (TEJ)-dominated pattern, with a secondary contribution from the intertropical convergence zone (ITCZ)-mediated pattern. The Indo-Pacific warming-induced TEJ strengthening favors a monopolar drying trend from 1950 to 2022, while the northward-shifted ITCZ drives a west drying-east wetting dipolar pattern. Considering an observational TEJ constraint, an accelerated TEJ with an amplitude of -2 standard deviations could cause an almost threefold increase in extreme drying trends in the near term (2026-2045). Instead, ITA could face a higher likelihood of extreme wetting tendency due to a near-term TEJ weakening. Our findings underscore the importance of realistic TEJ simulations in enhancing confidence in future precipitation projections across hydroclimate-vulnerable Africa. (200 words)

Introduction

The agriculture-dependent socioeconomic livelihoods in Africa are highly susceptible to precipitation variations during the boreal spring crop-growing season[1, 2] (March-May). Climatologically, intense spring precipitation predominantly occurs in the inter-tropical African domain[3] (ITA: 12°S-12°N, as demarcated in Fig. 1 and Supplementary Fig. 1), encompassing the Great Horn of Africa. Remarkable shifts in ITA spring precipitation regimes over historical intervals have sparked pivotal research interests. Decadal shifts in the spring precipitation regime in ITA have engendered multifaceted socioeconomic impacts[4], covering agriculture, economy, energy, ecosystems, the environment, and health. For instance, detrimental sequential droughts have swept ITA since the late 1990s (Fig. 1a and Supplementary Fig. 2), resulting in substantial losses of crop yields, livestock, and hydropower generation[5, 6] due to a decline in potable water and aquifer recharge[7] caused by rainfall deficits. These interlinked consequences push agriculture and pastoralist communities to the brink of acute food and freshwater shortages[8], with the United Nations declaring a near-famine emergency. Accordingly, it is imperative to understand the historical aspects and mechanisms of the ITA precipitation regime shifts to enable timely adaptation actions.

The observed ITA spring precipitation exhibits considerable inter-decadal fluctuations, characterized by a prominent wetting tendency before the late 1990s and a persistent drying trend thereafter through the 2020s (Fig. 1a), albeit with occasional interruptions in individual years. These alternate wetting and drying episodes are prevalent across various observations[2, 4, 9-13] and paleoclimate records[14-16]. Especially noteworthy is a spate of devastating droughts that have ravaged East Africa in recent decades, complicating the model-projected increase in precipitation response to greenhouse warming from the Coupled Model Inter-comparison Project (CMIP) of

previous generations[11, 13, 17, 18] (CMIP3, CMIP5, and CMIP6). The glaring observation-model incongruence is referred to as the East Africa climate paradox[11], triggering a dramatic debate on the underlying mechanisms. One primary hypothesis links the decades-long droughts to the unusual Indo-western Pacific sea surface temperature (SST) warming[1, 9, 19, 20] or tropical eastern Pacific cooling[2, 10, 18, 21-24] via the intensification of the Indian Ocean Walker circulation[20, 21]. The resulting enhanced subsidence suppresses precipitation in that area. Another hypothesis considers anthropogenic signals of East Africa drying, mainly due to the combined effects of greenhouse-gas-induced warming and aerosol-forced cooling, which increase evaporative demand[14, 25]. Nevertheless, the key mechanism governing historical changes in precipitation regime has not been rigorously quantified due to model deficiencies in reproducing the timing and magnitude of ITA precipitation changes.

Climate models from CMIP3 to CMIP6 consistently project increasing precipitation[13, 17, 18] in ITA over the past through the 21st century, casting doubt on near-term precipitation projections. To implement viable mitigation strategies across ITA, which is facing growing threats to food and water resource security, narrowing near-term projected precipitation uncertainty is indispensable, given a comprehensive understanding of the dynamics driving decadal shifts in the ITA precipitation regime. Here, we present observational evidence that two leading precipitation modes regulate decadal changes in observed ITA spring precipitation. The two modes are associated with the tropical easterly jet (TEJ) strengthening owing to Indian Ocean-western Pacific warming and a northward-shifted Inter-tropical Convergence Zone (ITCZ) modulated by a north-minus-south inter-hemispheric warming contrast, respectively, with the first mode being dominant. Our findings demonstrate that uncertainty in near-term projected ITA precipitation under high-emission scenarios greatly diminishes after correction using the observed TEJ.

Results

Two distinct precipitation regimes

We characterize observed spatiotemporal variations of ITA precipitation on inter-decadal timescales by applying an empirical orthogonal function (EOF) analysis to MAM-averaged precipitation anomalies in ITA (12°S-12°N, 16°W-52°E; excluding coastal or oceanic grids) during 1950-2022 (Methods). The first leading mode (~32.2% of the total variance) features a monopolar pattern of same-sign precipitation anomalies across ITA (Fig. 1b), except for a narrow strip along the coast of Equatorial Guinea. The corresponding principal component (PC1) delineates a gradual drop from 1950 to 2022, nearly in phase with the inter-decadal fluctuations of the observed TEJ strength (Fig. 1d). Because the first mode is strongly correlated with the TEJ, with a correlation coefficient of ~0.89 ($P < 0.01$), we refer to it as the TEJ-dominated precipitation regime. The second mode (~15.1%) resembles a northwest-southeast-oriented dipole-like pattern of opposite-sign precipitation anomalies (Fig. 1c). The corresponding time series are more synchronous with inter-decadal changes in the ITCZ location ($R = \sim0.58$, $P < 0.01$) and the north-minus-south inter-hemispheric temperature contrast ($R = \sim0.77$, $P < 0.01$), referred to as the ITCZ-mediated precipitation regime (Fig. 1e). Consistently, the TEJ-dominated monopolar and ITCZ-mediated dipole-like precipitation regimes are readily discernible from the Climatic Research Unit (CRU) high-resolution gridded precipitation dataset (Supplementary Fig. 3).

The two distinct precipitation patterns also manifest in other precipitation products from diverse data sources (Supplementary Fig. 4), albeit with spatial heterogeneity of precipitation variations. Furthermore, they are not highly sensitive to the size of the analyzed domain or shorter study periods (Methods). The broad agreement between two major modes across observations

confirms that the TEJ-dominated and ITCZ-mediated precipitation regimes adequately anchor inter-decadal variations in observed ITA spring precipitation. Based on the two distinct precipitation regimes, we reliably reconstruct the ITA spring precipitation anomalies for 1950-2022 (Fig. 1a), as corroborated by a high correlation with the original precipitation time series ($R = \sim 0.9$, $P < 0.01$). Notably, the original precipitation spatiotemporal variations better match the TEJ-dominated regime in terms of the decadal-timescale shifts (cf. Fig. 1a, d) and spatially homogeneous drying conditions inferred from the first-mode reconstruction alone (cf. Fig. 2a and Supplementary Fig. 2), indicating that inter-decadal changes in the ITA spring precipitation are principally controlled by the TEJ evolution (Fig. 1 and Supplementary Fig. 3), with an additional influence from a meridional excursion of the ITCZ.

Competing impacts of TEJ and ITCZ

We further unravel the dynamic processes for the dominance of TEJ over the large-scale precipitation decline pattern in ITA. We first quantify the observed ITA precipitation changes linearly congruent to the TEJ evolution by regressing the observed spring precipitation field onto the 9-year running-mean TEJ index and then multiplying the corresponding regression coefficients at each grid by the TEJ trends from 1950 to 2022 (termed TEJ-induced precipitation; see Methods). The accelerated TEJ reduces vertical moisture advection via anomalous subsidence (Fig. 2c, d), thus producing large-scale drying conditions across ITA (Fig. 2b and Supplementary Fig. 5).

To identify the robustness of the TEJ governing long-term precipitation changes in ITA, we decompose precipitation changes into dynamic (atmospheric circulation changes) and thermodynamic (atmospheric moisture content changes) components during 1950-2022 using the atmospheric column-integrated moisture budget[26, 27] (Methods). The long-term decline in net ITA

precipitation is strongly linked to decreased vertical moisture advection[28] (Fig. 2e), particularly the dynamic component induced by increased subsidence. More specifically, weakened vertical moisture advection linked to enhanced subsidence across large swaths of ITA contributes to the monopole-like drying pattern (Fig. 2f, g). The converse holds for positive precipitation anomalies in Equatorial Guinea. The physical consistency between the TEJ linear congruence and atmospheric moisture budget analyses demonstrates the dynamic control of TEJ in the long-term precipitation reduction over ITA (Fig. 2 and Supplementary Fig. 5).

The observed TEJ intensification is closely tied to enhanced equatorial planetary waves[29] for the period 1950-2022 (Supplementary Fig. 6), characterized by tropical tropospheric upper-level reversed-sign temperature signatures with significant warming at 200 hPa and cooling at 100 hPa (Supplementary Fig. 6c, d). Earlier studies have documented the linkage between increased equatorial planetary waves and SST anomalies in the Indo-western Pacific warm pool[29] or the tropical eastern Pacific[30-32]. To elucidate the origin of TEJ strengthening, we analyze three pacemaker experiments with CESM1 (Methods) wherein SST anomalies in the tropical Indian Ocean-western Pacific, tropical eastern Pacific, and North Atlantic are separately nudged toward observations. Anomalous spring warming across the tropical Indian Ocean-western Pacific and eastern Pacific creates an accelerated TEJ (-0.113 and -0.107 ms^{-1}/10yr in Supplementary Fig. 7), collectively explaining ~50% of the observed (-0.458 ms^{-1}/10yr) and thus suggesting increased equatorial planetary waves of similar tropospheric upper-level opposite-sign temperature structures to observations (cf. Supplementary Figs. 6-7). Conversely, North Atlantic warming weakens the TEJ.

Remarkably, tropical Indian Ocean-western Pacific warming stimulates anomalous easterlies occupying the tropical Indian Ocean-western Pacific and anomalous westerlies

traversing the tropical eastern Pacific-Atlantic Oceans. By comparison, tropical eastern Pacific warming generates easterly anomalies traversing the tropical Atlantic to the Indian Ocean (Supplementary Fig. 7). Such favorable circulation conditions intensify tropospheric upper-level easterlies[24], large-scale convergence, and subsidence across ITA (Supplementary Fig. 6g, h), consequently suppressing precipitation. These results of a causal chain highlight a major control of TEJ on long-term drying in ITA, which is quite distinct from the modulation of low-level easterlies[33-35] or the strengthening of the Indian Ocean walker circulation[20, 21] (Supplementary Fig. 8) on the inter-annual drying conditions in East Africa.

While an intensified TEJ caused by the Indo-Pacific warming directly governs a broad-scale long-term drying across ITA, a north-south swing of the ITCZ[36, 37] associated with inter-hemispheric thermal contrast indirectly stimulates a dipole-like precipitation pattern of inter-decadal changes (Fig. 3a-b and Supplementary Fig. 9). Anomalous north-minus-south inter-hemispheric SST gradients facilitate a northward-displaced ITCZ (Fig. 3a and Supplementary Fig. 9a) and a reduced Northern Hadley cell (Supplementary Fig. 10), coupling to the strengthened Walker cells across tropical oceans. The global reorganization of meridional- and zonal-overturning atmospheric circulations mirrors an energy balance between the increased northward oceanic heat transport from the Southern Hemisphere and the north-to-south cross-equatorial atmospheric heat flux[38, 39]. Correspondingly, cross-equatorial surface wind anomalies are well established. Accelerated easterlies over the tropical eastern Pacific transport moisture-rich air northward across the equator and join an anomalous cyclone within the subtropical North Pacific warm SST. The associated humid air deflects into the tropical Indian Ocean along the northwestern flank of the cyclone. Enhanced southeasterlies over the tropical Indian Ocean also advect moisture northwards and converge with the northwesterly flow from a weak cyclonic circulation linked to

the high surface temperature[12] over the Arabian Peninsula and Arabian Sea (Fig. 3b), eventually fueling more precipitation across East Africa and the northern Indian Ocean. By comparison, intensified westerlies across the equatorial Atlantic, alongside an anomalous cyclone linked to warming in the tropical North Atlantic and the Sahara, draw moisture southwards away from northwestern Africa and into South Africa, contributing to drying conditions in northwest Africa and wetting conditions over South Africa. As such, the contrasting inter-hemispheric moisture flows interact and jointly shape the dipolar pattern of northwest drying and southeast wetting.

The dipole-like precipitation pattern typically manifests in significant regression and correlation between spring precipitation anomalies and the ITCZ and north-minus-south inter-hemispheric SST gradient metrics (Fig. 3 and Supplementary Fig. 10). The mechanical robustness highlights the dynamic adjustment of the ITA dipole-like precipitation pattern in response to the inter-hemispheric temperature contrast through a meridional migration of the ITCZ. When the Northern Hemisphere is relatively warmer, the ITCZ-mediated precipitation anomalies exacerbate the TEJ-driven drying in northwest Africa but partly mitigate drying across East and South Africa (Fig. 3a). The reverse occurs for a comparatively warmer Southern Hemisphere. The spring inter-hemispheric thermal contrast during 1950-2022 probably results from spatially inhomogeneous anthropogenic aerosol emissions[40-42] (Supplementary Fig. 11), which indirectly mediates the inter-hemispheric ITCZ shifts through aerosol-cloud interactions[43].

An observational TEJ constraint on historical and near-term precipitation changes

Our results show that TEJ evolution associated with the Indo-Pacific warm pool warming modulates decadal changes in observed spring precipitation across ITA. Nonetheless, because the simulated TEJ strength and its decadal effect on ITA precipitation are comparatively weaker than

observations (Supplementary Fig. 12), two single-model and CMIP6 multi-model ensemble simulations over historical intervals and under high-emission scenarios reproduce a sustained wetting tendency, leaving near-term precipitation projections highly uncertain. Given the TEJ dominance over ITA spring precipitation, we can apply an observed TEJ constraint to correct historical precipitation changes and near-term projections. It is worth noting that our observational TEJ constraint framework preserves the coherence of the atmospheric energy and moisture budget in each member/model after adjustment. Within an energetic framework[44], we do not alter the column-integrated diabatic cooling and the dry static energy transport by the mean circulation, thus maintaining an equilibrium energy balance of the atmosphere and the surface. From a moisture budget perspective, we do not deteriorate the dynamic component linked to the mid-troposphere vertical velocity and the thermodynamic component related to the lower-troposphere moisture content (see Fig. 2).

We first quantify the influence of TEJ evolution on historical precipitation changes by replacing the simulated TEJ trend in each member/model with the observed TEJ trend for the entire period (1950-2022 for ERA5 and 1958-2022 for JRA55). When we substitute the TEJ-related precipitation changes in each member/model with those generated by the observed TEJ evolution (Methods), all the models congregate on a greater probability of aggravated ITA drying trends (Fig. 4a-c and Supplementary Fig. 13a-c). To further illustrate the impact of TEJ on the spatiotemporal changes in simulated precipitation, we select eight members/models that show the largest strengthening of the simulated TEJ decadal effect on ITA precipitation (Methods). After the observed TEJ adjustment, the simulated drying trends are broadly comparable to the observed TEJ-induced precipitation decline (Fig. 4d). The adjusted precipitation patterns in all modes more closely align with observations (Supplementary Fig. 14), particularly in East Africa.

In the near term (2026-2045), we might expect persistent droughts or a reversal to more precipitation under high-emission scenarios, as the TEJ evolution could completely negate or amplify the externally forced wetting response. To understand how the TEJ modulates evolving probabilities of near-term precipitation projections, we remove the simulated precipitation changes that are linearly congruent to the TEJ in each member/model (Methods). The standard deviations (SDs) of precipitation trends during 2026-2045 across all models substantially decrease by 19% to 39.7% (Fig. 4e), suggesting that uncertainty in near-term projected precipitation partially stems from the simulated TEJ evolution. Next, we estimate the SD of the observed TEJ in ERA5 during 1950-2022 (1958-2022 for JRA55) and assume that the TEJ will vary from -1SD to +1SD or between +1SD and -1SD. The TEJ evolution of 2SD for 2026-2045 (±1.1 ms^{-1}/10yr for ERA5 and ±0.73 ms^{-1}/10yr for JRA55) contains the observed TEJ trend (-0.4±0.08 ms^{-1}/10yr for ERA5 and -0.17±0.09 ms^{-1}/10yr for JRA55), thus representing a plausible future trajectory. We adjust the original TEJ-related precipitation changes in each member/model with those driven by the presumed fixed TEJ evolution (Methods). If a TEJ shifts from -1SD toward +1SD during 2026-2045, the chance of ITA drying will decrease from 44.44% to 36.84% (Fig. 4f), with a much higher likelihood of extreme wetting trends (11.11% to 28.07% in Fig. 4f and 11.11% to 16.96% in Supplementary Fig. 13d) compared to drying trends (9.94% to 19.88% in Fig. 4f and 9.94% to 15.79% in Supplementary Fig. 13d). By contrast, provided an accelerated TEJ with an amplitude of -2SD persists, the drying probability will greatly increase to 62%, with a nearly threefold increase in the chance of extreme drying trends (9.94% to 28.65% in Fig. 4f). The constrained near-term precipitation projections suggest a more likely drying future in hydroclimate-fragile Africa.

Discussion

ITA has experienced an extensive precipitation deficit since the 1990s, contrary to a model-projected past-to-future wetter response to anthropogenic warming[13] in CMIP6. Observed decadal shifts in the spring precipitation regime are primarily caused by the enhanced TEJ due to Indo-Pacific warm pool warming, with a secondary influence from the northward-shifted ITCZ linked to an anomalous north-minus-south inter-hemispheric warming contrast. Given the dominance of TEJ over ITA precipitation decadal changes, we propose an observational TEJ constraint framework to narrow model spread and uncertainty in historical and near-future precipitation changes. The evolving TEJ has exacerbated the decline in spring precipitation from 1950 to 2022 and is likely to further contribute to a drier future in the near term (2026-2045). These findings enhance confidence in minimizing risks associated with increased hydroclimate volatility[45] across Africa under greenhouse warming.

Our study raises an intriguing question: what modulates the observed TEJ strength? The spring TEJ intensity is highly correlated with the African easterly jet (AEJ; R = ~0.81, $P < 0.01$) and tropical Indo-western Pacific warm pool SST (R = -0.74, $P < 0.01$). As earlier studies have reported that the TEJ is less influenced by latent heat release linked to convection[46] and the AEJ is mainly regulated by the latitudinal temperature gradients between the Sahara and the Atlantic to the south[47], we may rule out the possibility of the TEJ-AEJ interactions. Additionally, the AEJ and TEJ evolutions produce distinct precipitation responses across the ITA. The accelerated AEJ transports horizontal moisture flux into the equatorial Atlantic and Congo basin from East Africa[33] and thus contributes to recent East African drying. However, the strengthened TEJ suppresses vertical moisture advection via anomalous subsidence (recall Fig. 2), leading to broad drying in ITA. Also, the TEJ strength is weakly correlated with the Northern Hemisphere-minus-Southern

Hemisphere inter-hemispheric internal contrast (R = -0.35, P < 0.05) and the meridional surface temperature contrast between North Africa and inter-tropical Africa (R = -0.4, P < 0.01). These observational arguments suggest that the TEJ intensification ultimately stems from remote forcing of tropical Indo-western Pacific warming.

While previous studies emphasize an anthropogenic origin of the Indo-western Pacific warming[48], climate models project a weakened TEJ under greenhouse warming (Supplementary Fig. 7a), in stark contrast to the Indo-Pacific warming-induced TEJ intensification observed in our pacemaker experiments. The seeming paradox suggests that the intensified TEJ emerges as a dynamic adjustment to Indo-Pacific warming rather than a direct response to greenhouse gases[46]. Current climate models misrepresent the bottom-up tropospheric processes[49] across the Indo-Pacific warm pool, thereby underestimating the simulated TEJ strength. Moreover, the simulated TEJ decadal effect on ITA precipitation changes is also substantially underestimated due to the weak connection of TEJ to ITA spring precipitation in climate models (Supplementary Fig. 12). Regarding our knowledge gap in regional climate dynamics[50, 51], systematic model biases[11], sparse rainfall-gauge observations[52], and intricate terrains[4] across ITA, convection-permitting high-resolution models[53] may provide an impetus to advance seasonal precipitation forecast capacities.

Due to unrealistic atmospheric and oceanic states in process-based modeling, skillful rainfall forecasts in ITA remain a challenge. Differentiable modeling[54], which combines physical models with machine learning, offers significant opportunities to bridge knowledge gaps and enhance predictive capabilities. This transformative approach could help deliver proactive climate information to disaster-prone African societies in a more interpretable, highly efficient way. An improved understanding of more plausible future trajectories of hydroclimate will benefit agrarian and pastoral practices in rain-fed Africa, which now faces an urgent need to formulate effective

adaptation actions to enhance the climate resilience of agriculture, infrastructure, and economic development.

Methods

Observations and reanalyses

Nine monthly precipitation products are analyzed here, including the European Centre for Medium-Range Weather Forecasts fifth-generation atmospheric reanalysis (ERA5)[55] on a 0.25°x0.25° horizontal resolution for 1950-2022, the Global Precipitation Climatology Center version 7 (GPCC)[56] with a 0.5°x0.5° grid for 1891-2020, the Climatic Research Unit TS version 4.09 (CRU)[57] with a 0.5°x0.5° grid for 1901-2022, the University of Delaware Terrestrial precipitation version 5.01 (UDEL)[58] on a 0.5°x0.5° grid for 1901-2017, the NOAA 20th-century reanalysis version 3 (20CV3)[59] with a 1°x1° horizontal resolution for 1806-2015, the Global Precipitation Climatology Project version 3.2 (GPCP)[60] on a 2.5°x2.5° spatial resolution for 1979-2022, the Climate Prediction Center Merged Analysis of Precipitation (CMAP) dataset[61] with a 2.5°x2.5° spatial resolution for 1979-2022, the 55-year modern Japanese Reanalysis (JRA55)[62] on a 1.25°x1.25° spatial resolution for 1958-2022, and the Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA2)[63] with a 0.5°x0.5° spatial resolution for 1980-2022. All datasets are linearly regridded to a common 1° x 1° resolution for visual purposes. These precipitation datasets are employed to examine the boreal spring precipitation climatology of 1981-2010 over inter-tropical Africa (ITA: 12°S-12°N, outlined in Fig. 1 and Supplementary Fig. 1), estimate long-term variations in the spring precipitation during 1950-2022 (Supplementary Fig. 2), and determine the spring precipitation dominant modes across ITA (Fig.1 and Supplementary Figs. 3-4).

Note that climatologically, prominent seasonal precipitation[3] mainly occurs across ITA. The ITA depicts bimodal rainfall variability during boreal spring and summer (July-September: JAS; Supplementary Fig. 1). Whilst current climate models simulate summer precipitation

variations in ITA over the historical interval[13, 17, 18] relatively well, they struggle to capture decadal shifts in the ITA spring precipitation regime, especially the past decades-long severe droughts (Supplementary Fig. 2). Additionally, historical precipitation projections of drought for southern Africa largely agree with the instrumental record[14]. Thus, our study mainly focuses on decadal shifts in the spring precipitation regime across ITA.

Atmospheric circulation, tropospheric temperature, and specific humidity fields from ERA5 and JRA55 are utilized to unravel the dynamical processes underlying two spring precipitation regimes (Figs. 1-2 and Supplementary Figs. 5-6). The Extended Reconstructed Sea Surface Temperature[64] version 3 (ERSST v3) on a 2°x2° grid, the Hadley Center Sea Ice and SST (HadISST) dataset[65] with a 1°x1° grid, the merged land-surface air temperature and SST dataset version 5 from the Met Office Hadley Centre (HadCRUT5)[66], and the National Oceanic and Atmospheric Administration (GlobalTemp)[67] during 1950-2022 are used to diagnose the north-south inter-hemispheric warming contrast that affects the ITCZ-mediated precipitation mode (Figs. 1 and 3 and Supplementary Figs. 9-11). Unless otherwise specified, our main results of the spring precipitation and atmospheric circulation diagnosis are based on ERA5 due mostly to its sufficient time length.

EOF analyses

We conduct an Empirical Orthogonal Function (EOF) analysis of observed spring precipitation anomalies over ITA (12°S-12°N, 16°W-52°E; excluding coastal or oceanic grids) in each dataset to extract the dominant variability in precipitation. Based on the North et al. criterion[68], the first two EOFs in ERA5, representing the TEJ-dominated and ITCZ-mediated precipitation patterns (Fig. 1 and Supplementary Fig. 3), are distinctly separated from the remaining eigenvectors and

totally explain ~47.3% of the inter-decadal variance. Although the ensuing five EOFs (from EOF3 to EOF7) also meet the criterion, their explaining variance substantially decreases from 7.9% to 2.3%. Thus, we primarily focus on the first two precipitation regimes, which strikingly capture the long-term and inter-decadal precipitation variability in ITA and are quite evident across different datasets and during different analyzed periods (Supplementary Figs. 3-4). Similar results are obtained from larger (15°S-15°N, 20°W-52°E or 20°S-20°N, 20°W-52°E or 40°S-20°N, 20°W-52°E) or smaller (10°S-10°N, 16°W-52°E) domains with and without coastal or oceanic grids selected to perform an EOF analysis.

After reconstructions from the two leading precipitation regimes, the time series of spring precipitation anomalies averaged over ITA are highly correlated with the original results (Fig. 1a), with a correlation coefficient of ~0.99 ($P < 0.01$). Moreover, when the first precipitation mode is incorporated solely into reconstructions, the reconstructed ITA spring precipitation shows a long-term drying trend (Fig. 2a), consistent with the observed broad-scale drying (Supplementary Fig. 2).

CMIP6 and single-model large ensemble simulations

Using 31 models participating in the Coupled Model Intercomparison Project phase six (CMIP6), we examine the historical simulations for 1950-2014 and future projections under the Shared Socioeconomic Pathway 2-Representative Concentration Pathway 4.5 (SSP2-4.5) for 2015-2022 and SSP5-8.5 for 2015-2100. Historical simulations are forced by both the natural and anthropogenic radiative forcings. Only the first realization for each model is analyzed. These multi-model simulations provide a quantitative evaluation of not only the climatology of and long-term changes in spring precipitation over ITA during historical periods (Supplementary Figs. 1-2)

but also the near-term projections (Fig. 4, Supplementary Figs. 11-14, and Supplementary Fig. 16). We also use two sets of large ensemble initial-condition simulations with CESM1 and MPI-ESM-LR from the US CLIVAR Working Group to provide the spring precipitation climatology and future projections (Fig. 4 and Supplementary Figs. 11-14). These single-model simulations are forced by historical radiative forcing for 1950-2005 and under the RCP8.5 for 2006-2100 following the CMIP5 (Ref. [69]). To assess the respective role of different forcings in driving the tropical easterly jet (TEJ) during 1950-2022, we investigate 10 CMIP6 models with single-forcing simulations from the Detection and Attribution Model Intercomparison Project[70], including all external forcing (All), aerosol-only forcing (Aer), and greenhouse-gas-only forcing (GHG) simulations. A detailed description of the models is listed in Supplementary Tables 1-2.

Time-evolving pacemaker experiments

To unravel the potential drivers of the observed TEJ strengthening from 1950 to 2022, we examine three sets of 10-member ensemble pacemaker experiments with the fully coupled climate model CESM1 using the earlier methodology[71, 72]. In these simulations (Supplementary Table 3 and Supplementary Fig. 15), SST anomalies over the tropical Indian Ocean-Western Pacific (IOWP: 15°S-15°N, African coast to 174°E with 5° buffer zones), tropical eastern Pacific (TEP: 15°S-15°N, 180° to the American coast with 5° buffer zones), and North Atlantic Ocean (NAT: 5°-55°N, the American coast to Africa/Europe with 5° tapering buffer zones) are separately restored to follow the observed history (ERSST V3). Beyond restoring domains, the ocean-atmosphere coupling systems are free to evolve. Each experiment is also forced by historical radiative forcing (1920-2005) and the RCP8.5 emission scenario (2006-2013), and initialized with micro-perturbations in the atmospheric conditions. The pacemaker experimental setup has reasonably reproduced the

three tropical ocean interactions[73] and tropical-southern ocean trans-hemispheric teleconnections[74], enabling us to systematically evaluate the extent to which SST variability in individual ocean basins forces the observed TEJ changes (Supplementary Fig. 7).

TEJ, ITCZ, and inter-hemispheric SST gradient metrics

The TEJ core resides near the equator in the boreal springtime for the climatology of 1981-2010 (Supplementary Fig. 5). Its location on the axis is largely unchanged for 1950-2022. The TEJ strength index[75] is expressed as the area-averaged 150-hPa zonal winds over the domain (8°S-8°N, 8°E-180°E). Negative values suggest a strengthened TEJ and vice versa. Note that climatological distributions of zonal winds, the strength, and the core axis location of TEJ are similar at 150 and 200 hPa levels. Thus, our main results are consistent for the TEJ defined based on 150-hPa and 200-hPa zonal winds.

To better understand factors regulating the TEJ intensity, we also discuss the relationship between the TEJ strength and the tropical Indo-western Pacific warm pool, the African easterly jet (AEJ), the inter-hemispheric thermal contrast, and the African meridional surface temperature contrast. The tropical Indo-western Pacific warm pool index is defined as the area-averaged SST (20°S-20°N, 30°E-180°E). The AEJ is defined as the area-averaged 700-hPa zonal winds (5°S-15°N, 10°W-20°E)[47]. The inter-hemispheric thermal contrast is defined as the difference in area-averaged surface temperature between (20°N-50°N, 0°-360°) and (20°S-50°S, 0°-360°). The African meridional surface temperature contrast is defined as the area-averaged surface temperature difference between northern Africa (15°N-30°N, 10°W-60°E) and inter-tropical Africa (12°S-12°N, 10°W-20°E).

We adopt the latitudinal centroid of tropical spring precipitation to measure the zonal-mean

location of the ITCZ[76]. Specifically, the ITCZ latitude ($\emptyset_{cent}$) is calculated from the weighting function, with an integer power (N) of the area-weighted spring precipitation (P) integrated between the latitudinal bounds ($\emptyset_1$=20°S and $\emptyset_2$=20°N) as follows:

$$\emptyset_{cent} = \frac{\int_{\emptyset_1}^{\emptyset_2} \emptyset[\cos(\emptyset)P]^N \, d\emptyset}{\int_{\emptyset_1}^{\emptyset_2} [\cos(\emptyset)P]^N \, d\emptyset} \quad (1)$$

Since the tropical precipitation centroid better captures the ITCZ variations across the seasonal to longer timescales[77-79], we use the tropical spring precipitation centroid (N=1) to determine its linkage to the ITA spring precipitation dipole-like pattern on inter-decadal timescales (Fig. 1c, e), with a correlation coefficient of ~0.58 (P<0.01). When N = 2, 3, or 4, the correlation coefficients are approximately 0.52, 0.46, and 0.41, respectively. The high correlation coefficients suggest that our main results are insensitive to the choice of N. The monthly precipitation is linearly interpolated to a 0.1° x 0.1° spatial resolution to minimize potential grid dependence before calculating the ITCZ centroid index. Our main results hold when integrating the domains equatorward of 15° and 30° in each hemisphere.

Previous studies have revealed that the seasonal migration of the ITCZ location is strongly linked to atmospheric heat transport at the equator (anticorrelation) and the inter-hemispheric tropical SST warming contrast (positive correlation) in both observations and coupled models[78]. For a visual comparison with the ITCZ-mediated precipitation regime (Fig. 1e), we calculate the north-minus-south inter-hemispheric SST gradient (NH-SH SST) as the difference between the area-weighted SST of 30°N-60°N minus -30°S-0°. Notably, the tropical SST mean (20°S-20°N) has been removed to accentuate the inter-hemispheric thermal contrast.

TEJ-induced precipitation changes

To quantify the direct impact of TEJ on long-term changes in the observed ITA spring precipitation,

we first regress the observed spring precipitation field onto the 9-year moving-mean spring TEJ index for 1950-2022. We then multiply regression coefficients at each grid by the TEJ time series to provide a projection of the spring precipitation field onto the TEJ index. Finally, we estimate linear trends for the corresponding projection, representing the spring precipitation trends statistically associated with the TEJ changes (Fig. 2b). We further apply the same procedure to the vertical moisture advection and 500-hPa vertical velocity (Fig. 2c-d and Supplementary Fig. 5) to unravel physical processes for the TEJ driving long-term drying across ITA.

Atmospheric moisture budget analysis

To disentangle the key physical processes governing ITA precipitation long-term changes related to the TEJ-dominated precipitation regime (Fig. 2), we partition precipitation changes into thermodynamic (atmospheric moisture changes) and dynamic (atmospheric circulation changes) components based on the atmospheric column-integrated moisture budget[26, 27] as follows:

$$P' - E' = -< \vec{V}_h \cdot \nabla_h q >' - < \omega \partial_p q >' + \delta' \quad (2)$$

where P and E are precipitation and evaporation, respectively; $\vec{V}_h$, ω, and q represent the horizontal and vertical pressure-level velocity and specific humidity, respectively; δ is a residual term largely because of sub-seasonal transient eddies, surface processes caused by the complex topography, and even moisture storage. The prime denotes the monthly anomaly referenced to the climatological mean of 1981-2010, and the angular brackets indicate vertical-column integration for the entire troposphere. Here, we aim to quantify the relative importance of different moisture advection terms to the effective atmospheric moisture ($P' - E'$).

The horizontal and vertical moisture advection terms are further split into:

$$-< \vec{V}_h \cdot \nabla_h q >' = -< \overrightarrow{\overline{V}_h} \cdot \nabla_h q' > - < \vec{V}_h{}' \cdot \nabla_h \overline{q} > - < \vec{V}_h{}' \cdot \nabla_h q' > \quad (3)$$

$$-<\omega\partial_p q>' = -<\overline{\omega}\,\nabla_h q'> -<\omega'\nabla_h\overline{q}> -<\omega'\nabla_h q'> \quad (4)$$

The terms on the right-hand side of the equations comprise thermodynamic components directly affected by temperature-generated changes in atmospheric water vapor following the Clausius-Clapeyron relationship, dynamic components tied to changes in atmospheric circulation, and nonlinear effects.

An observational TEJ constraint framework for precipitation changes

By replacing the simulated TEJ-related precipitation trends in each member/model with those driven by the observed TEJ, we establish a process-based constraint framework for narrowing the spread in simulated historical precipitation changes and reducing uncertainty in near-term precipitation projections (Fig. 4), similar to an adjustment method[80] of adopting the observed Inter-decadal Pacific Oscillation to constrain the simulated Indian summer monsoon precipitation. This process-based constraint framework is expressed as follows:

$$\partial_t P_{constrained}(j) = \partial_t P_{original}(j) - R_{P,TEJ}(j)\cdot(\partial_t TEJ(j) - \partial_t TEJ_{obs}), j = 1,2,\ldots,n \quad (5)$$

Where $\partial_t P_{constrained}(j)$ and $\partial_t P_{original}(j)$ are the constrained and original spring precipitation trends during the study period in member/model *j*, respectively; $R_{P,TEJ}(j)$ is estimated as the area-averaged regression coefficients of the ITA spring precipitation field against the 9-year running-mean spring TEJ index, reflecting the sensitivity of spring precipitation to the TEJ evolution (termed the TEJ decadal effect) in member/model *j*; $R_{P,TEJ}(j)\cdot\partial_t TEJ(j)$ is the original TEJ-induced precipitation trend in member/model *j* and $R_{P,TEJ}(j)\cdot\partial_t TEJ_{obs}$ indicates the precipitation trend related to the observed TEJ evolution.

To illustrate the potential impact of TEJ on near-term (2026-2045) spring precipitation projections (Fig. 4e), we compute the TEJ index in each member/model and then remove the spring

precipitation variations linearly congruent to the TEJ as follows:

$$\partial_t P_{non-TEJ}(j) = \partial_t P_{original}(j) - R_{P,TEJ}(j) \cdot \partial_t TEJ(j), j = 1,2,\dots,n \quad (6)$$

After removing the simulated TEJ effect on precipitation across models, the standard deviation of simulated precipitation trends in the near term (2026-2045) decreases from 19% to 39.7% (Fig. 4e), supporting our notion that a plausible TEJ evolution can effectively reduce near-term projected precipitation uncertainty.

Moreover, we estimate the probability of ITA drying during 2026-2045 (Fig. 4f). The chance of decreasing precipitation trends in ITA is computed by dividing the number of members showing negative precipitation trends by the total members (i.e., 31 CMIP6 models, 40 CESM1 runs, and 100 MPI-ESM-LR runs). We calculate the probability of near-term drying for both the original and the constrained precipitation trends under a given TEJ evolution. We also compute the probability of precipitation trends below the 10th percentile of the original trends (denoted extreme drying, ED) and above the 90th percentile (denoted extreme wetting, EW). The chance of ED (EW) is estimated by dividing the number of members showing precipitation trends less than (greater than) or equal to the 10th (90th) percentile of the original trends by the total members. The probabilities of ED and EW are also calculated for constrained precipitation trends with a certain TEJ evolution.

Statistical analysis methods

We employ an ordinary least-squares linear fit to estimate linear trends (Figs. 2 and 4) with a 95% significance based on a two-sided Student's *t*-test. A 9-year running mean is used to extract inter-decadal signals from observations and models before calculating regression and correlation coefficients. The statistical significance of regression and correlation coefficients is also measured

using a two-sided Student's *t*-test.

Data availability

Observations and model outputs used in this study are publicly available from the following websites: ERA5 (https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels-monthly-means?tab=download); GPCC (https://psl.noaa.gov/data/gridded/data.gpcc.html); CRU (https://crudata.uea.ac.uk/cru/data/hrg/); UDEL (https://psl.noaa.gov/data/gridded/data.UDel_AirT_Precip.html); 20CV3 (https://psl.noaa.gov/data/gridded/data.20thC_ReanV3.html); GPCP (https://psl.noaa.gov/data/gridded/data.gpcp.html); CMAP (https://psl.noaa.gov/data/gridded/data.cmap.html); JRA55 (https://rda.ucar.edu/datasets/ds628-1/); MERRA2 (https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/); ERSST v3b (https://www.ncei.noaa.gov/products/extended-reconstructed-sst); HadISST (https://www.metoffice.gov.uk/hadobs/hadisst/); HadCRUT5 (https://www.metoffice.gov.uk/hadobs/hadcrut5/); NOAA GlobalTemp (https://psl.noaa.gov/data/gridded/data.noaaglobaltemp.html); CESM1 large ensemble outputs are available at https://gdex.ucar.edu/gsearch/dataset-search/?q=CESM1+large+ensemble. All the CMIP6 model outputs are available at https://esgf-metagrid.cloud.dkrz.de/search. The CESM1 pacemaker experiments used in this study are available upon request.

Code Availability

The codes required to generate all the figures are available upon request. The codes are created using the NCAR Command Language (NCL: https://www.ncl.ucar.edu/).

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Author contributions

S.L.Y. and R.W. conceived the study and wrote the draft. S.L.Y. conducted all the data analyses and produced the final figures. P.L., P.S.C., and H.T. provided comments and revised the manuscript. P.W. helped edit the manuscript. All authors contributed to the interpretation of the results.

Competing interests

The authors declare no competing interests.

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Figure legends

Fig. 1 | Two leading regimes of spring precipitation changes in inter-tropical Africa on inter-decadal timescales. **a**, Temporal evolutions of spring precipitation anomalies for 1950-2022 relative to the baseline period of 1981-2010 over inter-tropical Africa (12°S-12°N, 16°W-52°E demarcated by the purple box in **b** and **c**) from ERA5. The blue line denotes the original precipitation anomaly, and color bars indicate the reconstructed precipitation anomalies based on two leading modes of the empirical orthogonal function (EOF) analysis (see Methods). **b, c**, The first (**b**) and second (**c**) principal patterns are obtained by applying an EOF decomposition into the MAM-averaged precipitation anomalies for 1950-2022 over inter-tropical Africa (12°S-12°N, 16°W-52°E; excluding coastal or oceanic grids) and represent the tropical easterly jet (TEJ)-related and inter-tropical convergence zone (ITCZ)-related precipitation regimes, which explain 32.2% and 15.1% of the total variance, respectively. **d**, The standardized 9-year running-mean time series of the TEJ-related precipitation regime (color bars) and TEJ index (blue) from ERA5. **e**, The standardized 9-year rolling-mean time series of the ITCZ-related precipitation regime (color bars) and ITCZ index (blue) from ERA5 and the north-minus-south inter-hemispheric sea surface temperature (NH-SH SST) gradient index (red) from ERSST v3. The tropical SST mean (20°S-20°N) has been removed before calculating the NH-SH SST gradient index.

Fig. 2 | TEJ-dominated spring precipitation changes in inter-tropical Africa. a, Linear trends of the TEJ-related precipitation pattern for 1950-2022 based on the first EOF reconstruction alone (Fig. 1b, d; see Methods). **b**, Precipitation trends statistically linked to TEJ changes for 1950-2022. The TEJ-related precipitation trends are estimated by projecting the observed spring precipitation field onto the 9-year running mean spring TEJ time series (Methods). **c-d**, As in **b**, but for spring

vertical moisture advection trends (**c**) and 500-hPa pressure vertical velocity trends (**d**). **e**, Linear trends of moisture budget terms averaged over ITA (12°S-12°N, 16°W-52°E) for 1950-2022, including precipitation (P'), evaporation (E'), zonal moisture transport ($-< udq >'$), meridional moisture transport ($-< vdq >'$), vertical moisture transport ($-< \omega dq >'$) and residual term ($residual'$). The precipitation minus evaporation ($P' - E'$) denotes the effective moisture. Vertical moisture advection comprises a thermodynamic component related to changes in atmospheric water vapor and a dynamic component caused by changes in atmospheric circulation (right two columns in **e**). **f**, Linear trends of spring vertical moisture advection during 1950-2022. **g**, As in **f**, but for spring 500-hPa vertical velocity trends. Stippling denotes regions where trends are statistically significant above the 95% confidence level, and error bars signify the 95% confidence interval based on a two-sided Student's *t*-test. Precipitation and atmospheric circulation data are derived from the ERA5 dataset.

Fig. 3 | ITCZ-mediated spring precipitation changes. a-b, spring precipitation (shading) and vertically integrated moisture flux (vector) (**a**), and surface temperature (**b**) are regressed against the 9-year running-mean time series of the ITCZ-related precipitation regime (color bars in Fig. 1**e**). **c-d**, Correlation coefficients of spring precipitation anomalies with the 9-year rolling-mean time series of ITCZ centroid index (**c**) and the north-minus-south inter-hemispheric SST gradient index (**d**), respectively. Surface temperature is from the NOAA merged land air temperature and ocean surface temperature. The north-south inter-hemispheric SST (NH-SH SST) gradient index from ERSST v3 is defined as the area-weighted SST difference between 30°N-60°N minus -30°S-0°. The tropical ocean (20S-20N) mean value has been removed to highlight the north-south inter-hemispheric warming contrast (**b**) before calculating the SST gradient index (**d**). Green lines (**a**

and **c-d**) denote the 6 mm/day contours of the climatological precipitation of 1981-2010. Stippling and vectors indicate regions where regression and correlation coefficients are statistically significant at the 95% confidence level based on a two-sided Student's *t*-test.

Fig. 4 | Constrained spring precipitation trends during 1950-2022 and for the near term (2026-2045) in ITA. a-c, Histograms of occurrence frequency of spring precipitation trends during 1950-2022 from 40 CESM1 runs (**a**), 100 MPI-ESM-LR runs (**b**), and 31 CMIP6 models (**c**) for original (orange) and adjusted (green) results accounting for the observed TEJ effect. Red (blue) dots represent the ensemble mean of trends with (without) the observed TEJ effect. Numbers signify the percentage of negative precipitation trends. **d**, Original (orange) and adjusted (green) trends for 1950-2022 are estimated from ERA5, observed TEJ-induced precipitation (Methods), as well as 8 CESM1 runs, 8 MPI-ESM-LR runs, and 8 CMIP6 models showing the largest strengthening of simulated TEJ decadal effect on precipitation. **e,** Trends during 2026-2045 under high-emission scenarios (RCP8.5 and SSP5-8.5). Light blue dots indicate the original trends, and pink dots denote the adjusted trends after removing the simulated TEJ effect. Error bars represent the 95% confidence interval based on a two-sided Student's *t*-test for observations and +/- 1SD of inter-member/inter-model precipitation trends for models. **f**, The fitted distributions of original (black) and adjusted (blue and red) precipitation trends for 2026-2045 from all models. Blue and red curves denote adjusted trends with the same amplitude as the observed TEJ due to a TEJ strengthening (-2SD per two decades) and weakening (+2SD per two decades), respectively. Black, blue, and red dots signify the ensemble mean of distributions with the corresponding colors. The green (brown) dashed line denotes the threshold of the probability of extreme wetting (drying) trends.