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Weakened seasonality of the African rainforest precipitation in boreal winter and spring driven by tropical SST variabilities

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Abstract

Precipitation in the equatorial African rainforest plays an important role in both the regional hydrological cycle and the global climate variability. Previous studies mostly focus on the trends of drought in recent decades or long-time scales. Using two observational datasets, we reveal a remarkable weakening of the seasonal precipitation cycle over this region from 1979 to 2015, with precipitation significantly increased in the boreal winter dry season (~0.13 mm/day/decade) and decreased in the boreal spring wet season (~0.21 mm/day/decade), which account for ~14% (the precipitation changes from 1979 to 2015) of their respective climatological means. We further use a state-of-the-art atmospheric model to isolate the impact of sea surface temperature change from different ocean basins on the precipitation changes in the dry and wet seasons. Results show that the strengthening precipitation in the dry season is mainly driven by the Atlantic warming, whereas the weakening precipitation in the wet season can be primarily attributed to the Indian Ocean. Warming Atlantic intensifies the zonal circulation over the African rainforest, strengthening moisture convergence and intensifying precipitation in the boreal winter dry season. Warming Indian Ocean contributes more to reducing the zonal circulation and suppressing the convection in the boreal spring wet season, leading to an opposite effect on precipitation. This result has important implication on local ecology as well as global climate system.

Keywords: Seasonality of precipitation, African rainforest, Walker circulation, Convergence of moisture

Introduction

African rainforest, located in the Congo Basin, is the world's second-largest tropical forest region (Malhi et al. 2013; Mayaux et al. 2013; Fig. 1a). Rainforests play important roles in hydrology and carbon storage due to their rich biodiversity and high ecological function (Baccini et al. 2012; Saatchi et al. 2011). African rainforest is one of three key convective regions, and the other two are Maritime Continent and Amazon basin (Washington et al. 2013; Todd and Washington 2004). Deep convection and diabatic heating over three regions drive the global tropical circulation (Hart et al. 2019; Webster 1973), which make great contributions to the global climate system. In addition, deep convection over the African rainforest is larger than any other region in the global tropics, dominating the global tropical rainfall distribution in the transition seasons (Washington et al. 2013). However, long-term drying trend occurred over the equatorial western and central Africa (Asefi-Najafabady and Saatchi 2013; Diem et al. 2014; Hua et al. 2016; Malhi and Wright 2004; Yin and Gruber 2010), resulting in a declining of Congo rainforest greenness and altering the forest structure (Chambers and Roberts 2014; Zhou et al. 2014). Therefore, it is crucial to understand the change of climate in African rainforest regions, in particular precipitation in different seasons.

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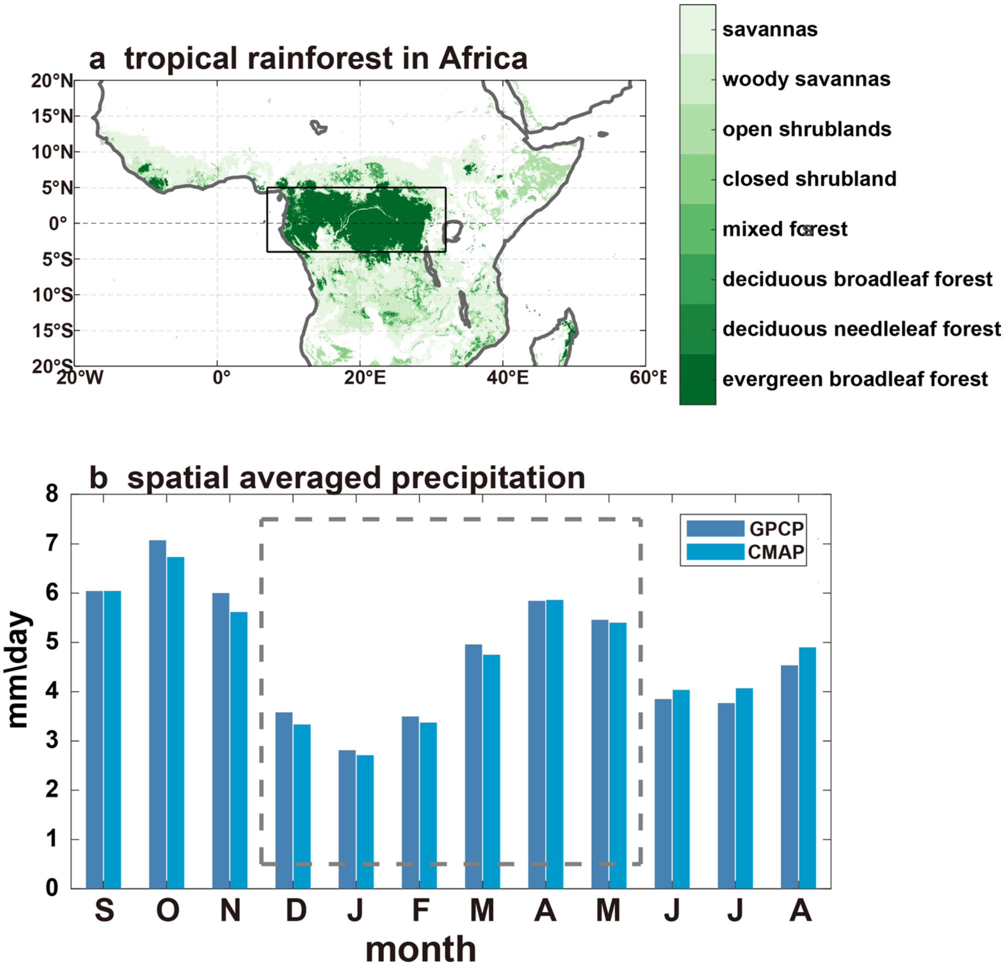

Fig. 1 African rainforests and monthly mean precipitation. **a** The distribution of tropical African rainforest, based on 2011–2015 MCD12C1 datasets. In this study, we focus on the domain (7°E-32°E, 4°S-5°N, the box), covering the most of African rainforest. **b** The spatial averaged (the box in **a**) climatology of monthly precipitation, based on 1979–2015 GPCP and CMAP datasets

Rainfall in equatorial Africa is affected by the shift of the intertropical convergence zone (ITCZ, Nicholson 2018; Sultan and Janicot 2000) and is related to West African monsoon (Nicholson 2009; Redelsperger et al. 2006; Thorncroft et al. 2011) and local zonal circulation (Leduc-Leballeur et al. 2013; Nicholson and Dezfuli 2013; Williams and Funk 2011). An upward branch of Walker circulation over the Congo Basin and a downward branch over the Gulf of Guinea play important roles in the process of precipitation over the West Africa (Cook and Vizy 2016). Deep convection caused by ascending motion over the Congo Basin is positively associated with precipitation in West Africa (Cook and Vizy 2016) while subsidence makes a contribution to maintain moisture transport into this region (Dezfuli et al. 2015). Some regional factors, such as topography, mid-level jets, and mesoscale convective systems all influence precipitation (Jackson et al. 2009; Nicholson 2009; Pokam et al. 2012). Under the impact of these complex factors, the seasonal cycle of equatorial African precipitation is characterized by a bimodal feature, with two rainy seasons (March, April, May, MAM; September, October, November, SON) and two dry seasons (June, July, August, JJA; December, January, February, DJF) (Creese and Washington 2018; Washington et al. 2013; Fig. 1b).

There is a seasonal difference in driving the variation of regional precipitation by sea surface temperature (SST) forcing (Balas et al. 2007; Farnsworth et al. 2011). On intraseasonal timescales, the equatorial SST cooling plays a role in the precipitation along the African coast during boreal spring (Leduc-Leballeur et al. 2013). On interannual timescales, Atlantic SST governs the movement of the ITCZ and further influence boreal summer precipitation in equatorial Africa (Nicholson 2009). The Indian

Ocean is more related to rainfall in late summer/early fall, whereas Pacific is important for central Africa in MAM (Balas et al. 2007; DiNezio et al. 2013; Farnsworth et al. 2011). However, ENSO is less directly connected to African rainforest precipitation (Malhi and Wright 2004). Long-term drought in West and Central Africa is mainly linked to the change of Atlantic circulation (Shanahan et al. 2009) and SST (Camberlin et al. 2001; Diem et al. 2014), and warming Indian Ocean also makes an important contribution (Diem et al. 2014; Hoerling et al. 2006; Hua et al. 2016; Richard et al. 2001). In boreal winter/spring season, tropical North Atlantic may force anomalous circulation and increased precipitation in central equatorial Africa (Todd and Washington 2004). Additionally, Pacific SST can also modulate precipitation over eastern and southern Africa by atmospheric bridge (Dezfuli et al. 2013; Hua et al. 2016; Maidment et al. 2015).

Previous studies indicated that long-term dry trend caused the shrinking of Congo rainforest (Zhou et al. 2014). It is also reported that the dry season (JJA) length has been increased by 6.4–10.4 days per decade in the period of 1988–2013 over the Congo rainforest (Jiang et al. 2019), which is mainly relates to an earlier dry season onset and a delayed dry season end. The decreased precipitation during AMJ (April, May, June) result in the decline of soil moisture and further cause the longer boreal summer (JJA) dry season over the Congo rainforest (Jiang et al. 2019). In East Africa, the precipitation in MAM (defined as "long rains") decreased due to abrupt change of tropical Pacific SST (Lyon and DeWitt 2012). In addition, anthropogenic forcing has influenced the decreasing trend in rainfall over the northern African monsoon to a great extent (Ha et al. 2020). However, changes in extreme precipitation events in the dry season (JJA) of the Congo Basin do not come from an anthropogenic climate signal (Otto et al. 2013). Many efforts have been devoted to study the precipitation in dry and wet seasons under global warming and found models show large uncertainties (Creese and Washington 2018; James et al. 2013). Up to now, most of these studies concentrate on either one season or the projection of models in African rainforest precipitation. However, the change in seasonalities between dry and wet seasons in recent decades is not very well investigated because of extremely limited observation stations. Meanwhile, the mechanism causing the change of precipitation seasonality remains unclear.

In the rest of this paper, we focus on the recent decadal trend in dry season of boreal winter (DJF) and boreal spring wet season (AM) over the equatorial African rainforest region, by combining observed datasets and atmospheric model simulations. We describe the datasets, the statistical methods, and the model experiments in "Methods" section, and examine the observed recent long-term trends in the dry and wet seasons in "Results" section. We found that the seasonality of precipitation over the African rain forest is weakening over the past ~ four decades, i.e., precipitation has significantly increased in the boreal winter dry season and decreased in the boreal spring wet season. Further, we investigate the impacts of tropical SSTs on the observed precipitation changes using atmospheric model simulations in "Results" section. The change of specific humidity, moisture flux and Walker circulation forced by SST over the African rainforest region are presented in "Results" section. Finally, conclusions and discussions are given in last section.

Methods

In this study, we use MODIS land cover map dataset (MCD12C1, Friedl et al. 2010) to describe the distribution of the African rainforest. To examine the precipitation change, we used two observed precipitation datasets, the Global Precipitation Climatology Project (GPCP, Huffman et al. 2009) and the CPC Merged Analysis of Precipitation (CMAP, Xie and Arkin 1997). These datasets are based on gauge stations and satellite observations, and are widely used as reliable precipitation measurements (Yin et al. 2004). The pattern of tropical SST in recent decades has an important impact on precipitation change. To investigate observed SST changes in different basins, we use the Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST, Rayner et al. 2003). The same dataset was also used to drive the atmospheric models.

In addition, as the African rainforest is mainly distributed in the equatorial Congo Basin and is characterized by seasonal wetting–drying cycles, we calculate the changes of precipitation over the rainforest (7°E-32°E, 4°S-5°N) in the boreal winter dry season (DJF) and boreal spring wet season (AM) from 1979 to 2015. The Sen's slope method (Sen 1968) are adopted to calculate observed and simulated trends, and their confidence intervals was estimated using a Mann–Kendall test (Richard 1987). These two methods are non-parametric and robust in the existence of outliers. For the following model simulations, we also use the same method to analyze.

To understand the mechanism of precipitation change, we examine the trend of Walker circulation and moisture by using Sen's slope. Walker circulation is based on zonal mass stream function, is given by Yu and Zwiers (2010) and Yu et al. (2012):$\Psi = \frac{a\Delta\varphi}{g}\int_0^{\mathrm{p}} u_D dp$, where Ψ is the zonal mass stream function, a is the Earth radius, $\Delta\,\varphi$ is the width of the 5°S–5°N band along the equator in radians, g is the gravitational acceleration,u_D is the divergent component of the zonal wind, and p is the pressure. In addition to analyzing the moisture and wind at 825 hPa, we also calculate the divergence of vertically integrated moisture flux (Satyamurty et al. 2013), defined as $D_w = \nabla \cdot F_w$, $F_w = \int q\mathbf{V}\mathrm{d}p/g$. $\mathbf{F}_{\mathrm{W}}$ is vertically integrated moisture flux. q is specific humidity, V is vector wind, and p is pressure. The moisture fluxes are integrated from the surface to 300 hPa because water vapor content above 300 hPa is negligible. One of the focuses of this study is how the SST change in tropical basin in the recent decades influences African rainforest precipitation. However, different basins interact with each other on interannual and decadal timescales. Results in atmospheric models do not reflect inter-basin interaction, and are thus typically used to isolate the role of different basins. As a result, the NCAR atmospheric model, Community Atmosphere Model version 4 (CAM4, Neale et al. 2013) is used to investigate the atmospheric responses to the observed SST trend in different ocean basins. The finite volume dynamical core is used in CAM4 models with F19 horizontal resolution (~ 2°). We designed three SST forcing experiments by the tropical Atlantic, Indian and Pacific Ocean, respectively. Given the importance of the inter-basin interactions, we also designed the experiment forced by the observed SST variability over the tropical ocean. The model is forced by observed SST variability from 1979 to 2015 in the target basin, while the model is driven by climatological SST in the other basins. The configuration of each target basin is the tropical ocean region from 20°S to 20°N, i.e., Atlantic Ocean between 20°S and 20°N, Pacific Ocean between 20°S and 20°N, and Indian Ocean between 20°S and 20°N. Buffer regions are 30°S–20°S and 20°N–30°N in each experiment. Strength of SST forcing over buffer regions is gradually reduced. In addition, the SSTs outside of the tropical region are fixed to the climatological value. There is no coupling outside of the tropical region in the model. We conducted 12-member ensemble simulations in the experiments for each ocean basin. The 12-member ensemble simulations are generated by slightly different observed SST trend in each target basin. By examining the change of the ensemble-mean, we could understand the contribution to precipitation change by the individual ocean basin.

Results

Observed changes in African rainforest precipitation

Given regional distribution of African rainforest, we focus on the domain marked by black box in Fig. 1a (7°E-32°E, 4°S-5°N). We further calculate the climatology of area-averaged precipitation in each month (Fig. 1b). As suggested in previous studies, a typically bimodal seasonal precipitation feature is apparent in this region. The boreal winter (DJF) is a clear dry season, with climatological precipitation of 3.15–3.31 mm/day. In the next few months, climatological precipitation starts to exceed 5 mm/day, which means wet season is coming. In particular, in April and May, the rainforest receives the highest precipitation in the first half of the year. In addition, Jiang et al (2019) had revealed that the earlier dry season (JJA) onset was related to the change of precipitation during the AMJ over the Congo basin. Accordingly, we only choose the boreal winter dry season (DJF) and boreal spring wet season (AM) to examine the seasonality of precipitation over the African rainforest regions in past decades. Without special explanation, the boreal winter dry season is DJF and the boreal spring wet season is AM in later sections.

Figure 2 shows the observed precipitation trend in the boreal winter dry season (Fig. 2a, b) and boreal spring wet season (Fig. 2c, d) from 1979 to 2015. Remarkably, two observational datasets show similar spatial patterns, with a significant increasing (deep green color) trend in DJF and a decreasing trend (deep brown color) in AM. In the dry season, the largest positive precipitation trends are mainly distributed in the west and east of the domain (Fig. 2a, b). However, in the wet season, stronger negative precipitation trends are not confined to the eastern rainforest, but widely extended to East African Plateau (Fig. 2c, d). Observations exhibit an opposite sign of trend in two seasons, whereas the drought in the boreal spring appears to be more extensive. We also analyzed the precipitation trends from 1979 to 2019 (Additional file 1: Fig. S1). The trends in observations over African rainforest do not change much when extended to 2019.

Observed patterns indicate different amounts of precipitation change during the boreal winter dry season and boreal spring wet season (Fig. 2). Therefore, we show the quantitative features of precipitation in Fig. 3. The results of GPCP and CMAP are nearly identical. Time series of precipitation show an increasing in DJF (Fig. 3a) and a decreasing in AM (Fig. 3b) since 1979. Spatially averaged precipitation trends over the rainforest region (Fig. 3c) suggest that the observed precipitation anomalies are statistically significant at the 5% level, with magnitudes of ~ 0.13 mm/day/decade in DJF and ~ 0.21 mm/day/decade in AM.

All observational datasets show a dramatic weakening of seasonality of precipitation over Africa rainforest region. Seasonal precipitation changes from 1979 to 2015 account for 14% of their respective climatological means (~ 3.23 mm/day in DJF and ~ 5.65 mm/day in AM). To a large extent, the change of convective precipitation is modulated by tropical SST. In past decades, three tropical ocean basins experience different SST trends, namely a warming in the Atlantic,

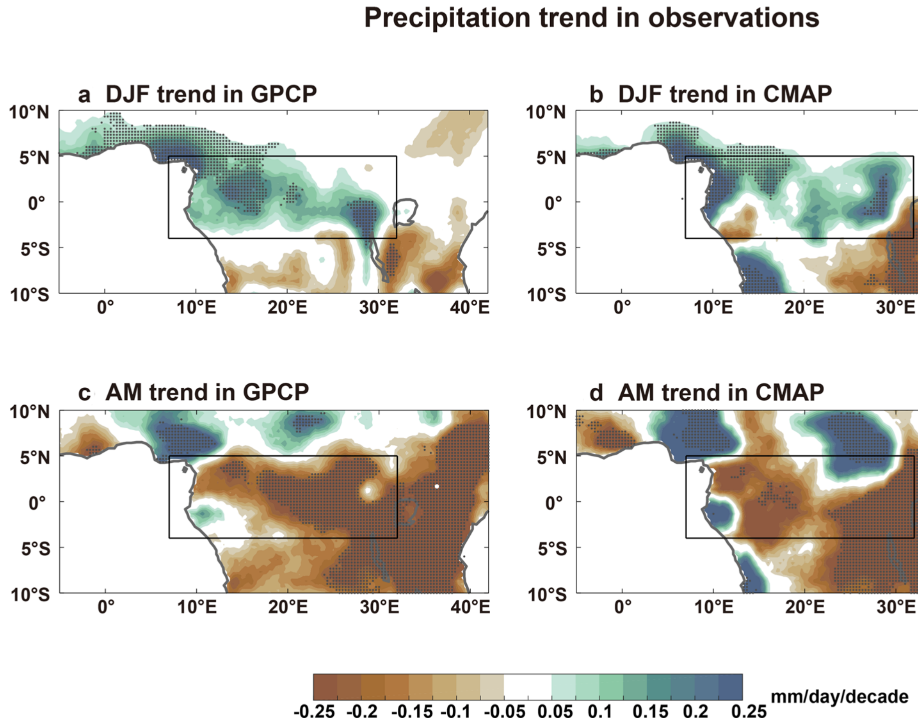

Fig. 2 Seasonal precipitation changes in observational datasets from 1979 to 2015. Color mapping represents the precipitation change (increase, dark green; decrease, dark brown). Dark dots indicate that precipitation trends are significant at the 5% level. Upper panels (**a**, **b**) show the precipitation change during the boreal winter dry season (DJF) from GPCP and CMAP. Lower panels (**c**, **d**) same as **a**, **b** but for the boreal spring wet season (AM)

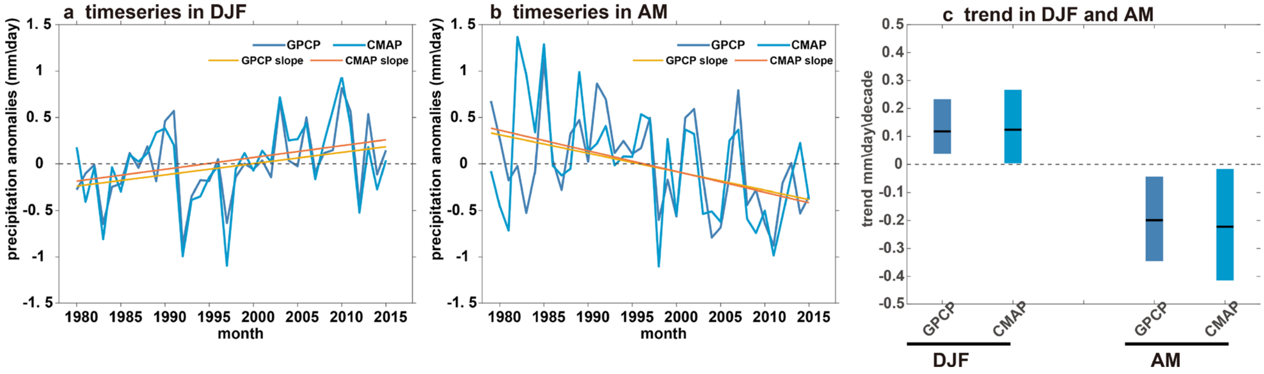

Fig. 3 The statistics of spatial averaged precipitation in observations. **a**, **b** Time series of observed precipitation anomalies over the African rainforest (dark box in Fig. 2) show an intensified tendency during the boreal winter dry season and a weaken tendency during the boreal spring wet season. **c** The black lines and thick bars represent precipitation change and 95% confidence intervals

Indian and western Pacific Ocean, and a cooling in central-eastern Pacific (Kosaka and Xie 2013; Li et al. 2016; McGregor et al. 2014). SST changes can be further attributed to the positive phase of the Atlantic Multidecadal Oscillation (AMO) and the cooling phase of the Pacific Decadal Oscillation (PDO; Kamae et al. 2017). These SST trends play key roles in changing regional or global climate. In particular, the warming of Atlantic and Indian Ocean may be more relevant to the change of precipitation in Africa. Therefore, we use atmospheric models to conduct experiments in order to quantify contribution of individual ocean basins to tropical African precipitation.

Impacts of tropical SST variabilities on the precipitation changes

We first examine observed DJF and AM decadal SST trends (Fig. 4). As revealed in many studies, Atlantic and Indo-western Pacific show an apparent warming, but central-eastern Pacific shows an evident cooling. However, the amplitude of SST trends varies with season. The magnitude of warming in Atlantic and cooling in central-Pacific in DJF is larger than that in AM, which may exert different effects in the corresponding season. Next, we add observed SST variability into the target basin to drive model and climatological SST in other ocean basins are used to drive model.

In order to test and to verify the simulation of atmospheric models, we compare the observed and simulated precipitation climatology (Fig. 5 and Additional file 1: Fig. S2). In the boreal winter dry season and boreal spring wet season, the climatological pattern is reasonably reproduced by models, such as spatial distribution and transition of dry and wet season, although models usually

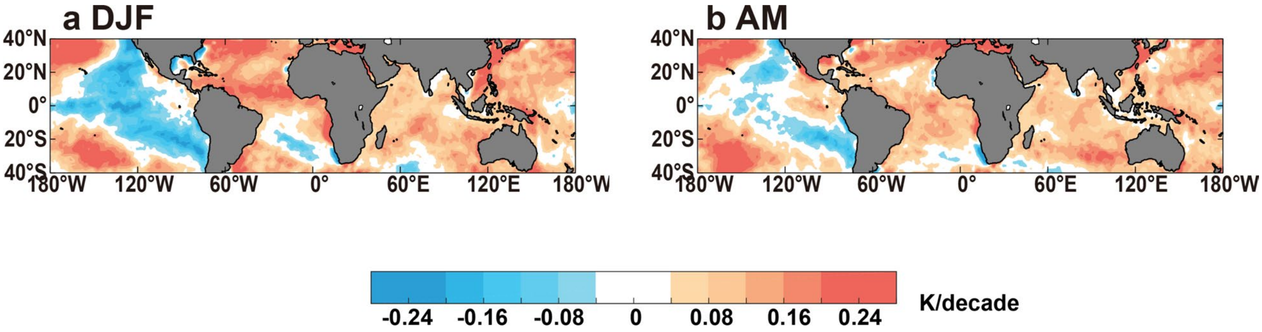

Fig. 4 Observed seasonal HadISST trend from 1979 to 2015. **a**, **b** Color mapping represents decadal SST change in DJF and AM

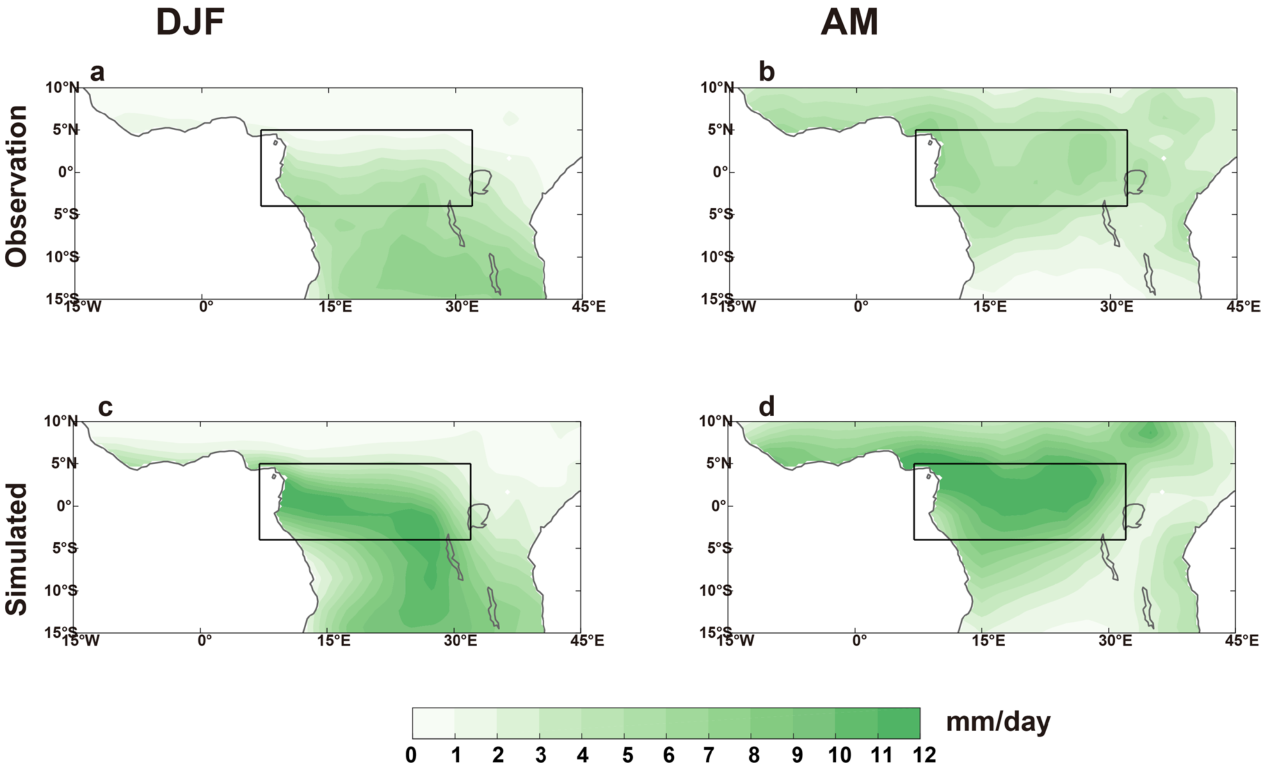

Fig. 5 Climatological precipitation pattern in observation and simulated. Upper panels (**a**, **b**) show observed (the mean of GPCP and CMAP) climatology in DJF and AM. Lower panels (**c**, **d**) same as **a**, **b** but for the AM

slightly overestimate precipitation. In addition, we examine the climatology of area-averaged precipitation in models from December to June (Additional file 1: Fig. S3). The seasonal cycle is reasonably reproduced, despite simulated heavy rainfalls in these months. We also calculated the standard deviation of precipitation (Additional file 1: Fig. S4). The variability over the domain in observations is smaller than that in models, especially in the boreal spring wet season. Further, we simulate the change of precipitation by running these models.

Forced by tropical SST, the precipitation changes in the domain are not well reproduced (Additional file 1: Fig. S5). However, simulated area-averaged precipitation trends are mainly characterized by wet (increased ~ 0.02 mm/day/decade) during the boreal winter dry season and drought (decreased ~ 0.13 mm/day/decade) during the boreal spring wet season from 1979 to 2015. Figure 6 displays the precipitation trends by forcing three ocean basins: the tropical Atlantic, Indian and Pacific, respectively. During the boreal winter dry season, the model responses to the tropical Atlantic show the closest resemblance to the observation (Fig. 6a, the pattern correlation of precipitation change in Additional file 1: Table. S1), while the responses to tropical Indian and Pacific Ocean are opposite to those in observations (Fig. 6b–c). Regional difference is obvious although the model (forced by Atlantic SST) simulate the enhanced precipitation trend. Observation increased precipitation mainly appears in the North of domain. However, the model responses to the Atlantic forcing display the strong positive trend in most of southern region. Overall, forced by tropical Atlantic Forcing, the model reproduces the strengthening pattern in central and western rainforest (Fig. 6a), implying that the Atlantic plays a leading role in the wetting in DJF while Indian and Pacific Ocean have completely opposite effect.

During the boreal spring wet season, significant negative anomalies appear over the African rainforest in three ocean forcing experiments. There was a certain degree of difference in the precipitation trend distribution between observations and modes (Fig. 6d–f). Reproduced decreased trends are mainly located in northwestern rainforest, albeit with enhanced trends in the southwest part. However, the amount and scope of drought are simulated by Indian and Pacific Ocean seem to be larger (Fig. 6e–f). Compared with observed trend in AM, the model responses to Indian Ocean forcing show the smallest magnitudes of increased precipitation over the southwest region (Fig. 6e) and model responses to Pacific forcing show the drying trend over the southeast region (Fig. 6f). These results indicate that Indian and Pacific Ocean have more important impacts on the drying in the AM.

The simulations in atmospheric models emphasize that the individual ocean basin has different impacts on African rainforest rainfall in the boreal winter dry season and boreal spring wet season. The enhanced precipitation in DJF is mainly attributed to the warming Atlantic forcing,

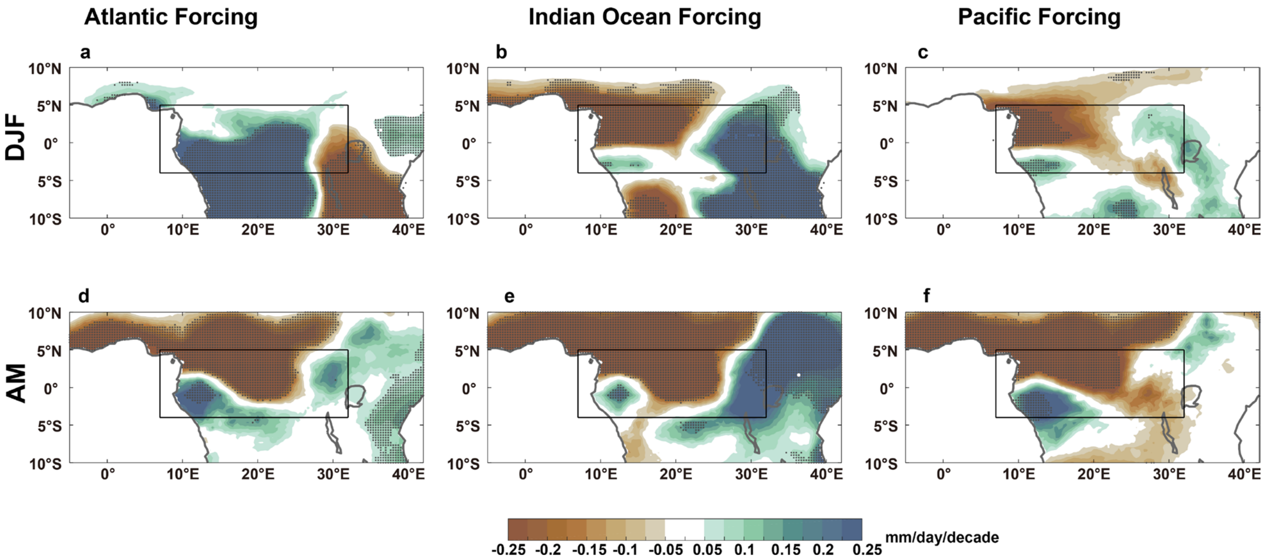

Fig. 6 Simulated seasonal precipitation change from 1979 to 2015 in atmospheric models. Color mapping represents the precipitation change (increase, dark green; decrease, dark brown). Dark dots indicate that precipitation trends are significant at the 5% level. **a**–**c** show the precipitation change during the boreal winter dry season (DJF) forced by the tropical Atlantic, Indian Ocean and Pacific SST. **e**–**g** same as **a**–**c** but for the boreal spring wet season (AM)

whereas the Indian and Pacific Oceans produce an opposite effect. The weakening precipitation in AM is driven by all three oceans, with Indian and Pacific Ocean making more contributions. Our numerical experiments show that individual SST forcing has important contributions in driving the change of precipitations over the equatorial African rainforest despite some differences in the simulated and observed trend. Especially in the boreal winter dry season, Atlantic SST forcing captures the increased precipitation trend, whereas Indian and Pacific SST forcing produces the opposite. As a result, the total simulated trend is not very similar to the observed. Interbasin interactions may play important roles in causing the differences. Three basins are tightly connected and interacted by atmospheric bridges. Indian and Pacific SST could potentially affect the precipitation by inter-basin interactions. The linear effect of individual tropical oceans is relatively simple, whereas the combining effect of three ocean basin is extremely complex. Some nonlinear effects in model simulation are not very well established. In this study, we explore the roles of individual SST in driving equatorial African precipitation from a linear framework. Some nonlinear effects including inter-basin interaction are needed to be investigated.

Mechanisms of the precipitation changes

Because African precipitation can be affected by the strength of the Walker circulation (Cook and Vizy 2016; Hua et al. 2016), we examine changes of the latter to clarify the processes that link precipitation over the African rainforest and tropical SST. Figure 7 shows the zonal mass stream function (Walker circulation) trend (shading) and climatology (contour) over the equatorial Africa in atmospheric models. And the divergent component of the zonal wind in stream function is averaged between 5°S and 5°N. During the boreal winter dry season (DJF), significant positive trends appear in the core region of climatology simulated by Atlantic forcing (Fig. 7a), whereas negative trends appear under Indian Ocean forcing (Fig. 7b). Enhanced circulation associated with deep convection is closely linked to higher rainfall in DJF. During the AM, only Indian Ocean generates significant negative trends (Fig. 7e), with weakening circulation and less precipitation. Pacific forcing has no clear sign in either

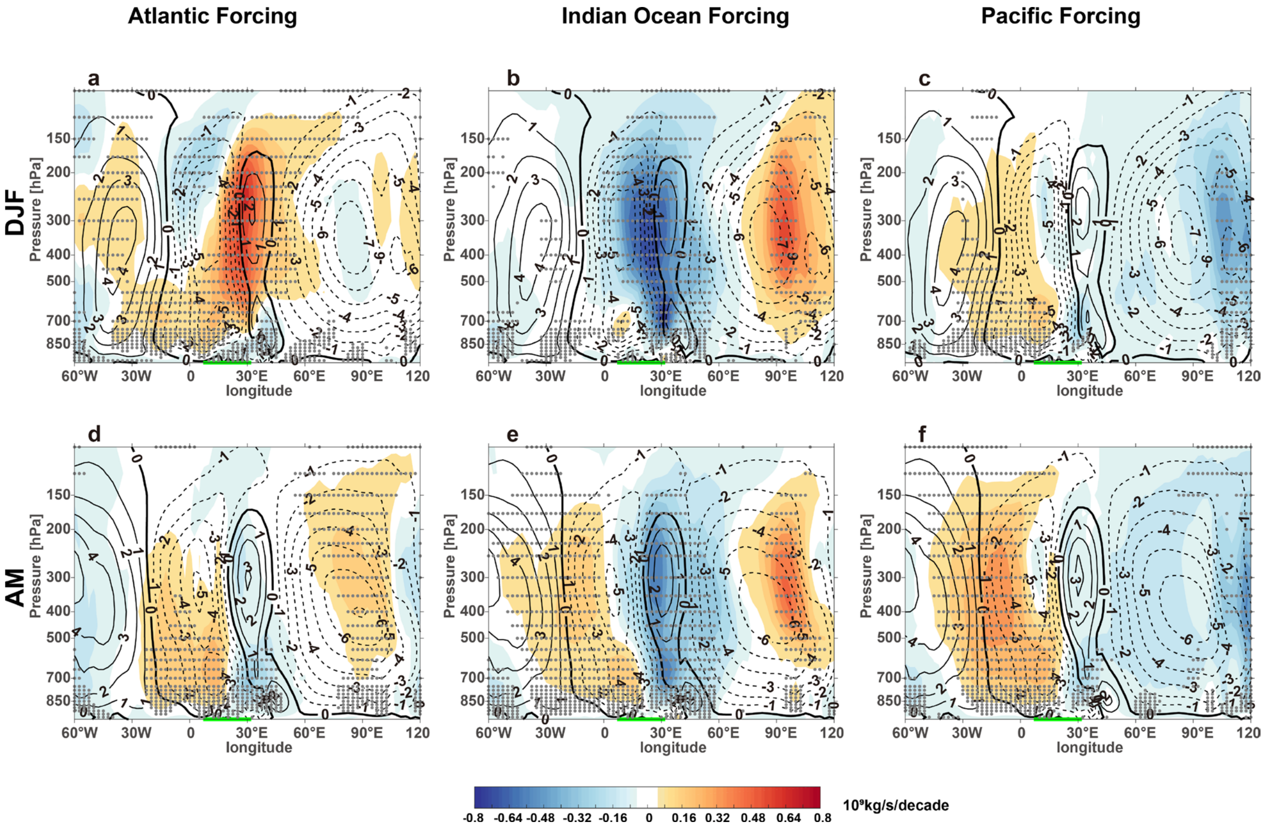

Fig. 7 Simulated seasonal change of Walker circulation in atmospheric models from 1979 to 2015. Color mapping illustrates the circulation change and contour show the climatology. **a**–**c** show the pattern forced by the tropical Atlantic, Indian Ocean and Pacific during the boreal winter dry season (DJF). **d**–**f** same as **a**–**c** but for the boreal spring wet season (AM). Green lines are the African rainforest region

season (Fig. 7c, f). The strengthening (weakening) circulation is coherent with increased (decreased) precipitation in simulations.

SST is important driver for the changes of atmospheric circulation. In addition, SST forcing in different tropical basins also modulate the changes of precipitation by affecting the process of moisture. Changes of specific humidity and moisture flux convergence reflect evolutions in moisture, energy and convection in the air, which are intimately connected with precipitation (Chadwick et al. 2016; Gaffen and Ross 1999; Trenberth et al. 2011). Figure 8 shows the simulated anomaly specific humidity (moisture; color) and moisture flux (arrows) at 825 hPa. During the boreal winter dry season, strengthening moisture anomalies accompanied by typical convergence over the equatorial western African are driven by the tropical Atlantic forcing (Fig. 8a). However, forced by Indian and Pacific Ocean, simulations show the weakening moisture trend over the central and western part of the domain (Fig. 8b–c). Meanwhile, anomaly moisture flux show the divergence over the equatorial western Africa (Fig. 8b–c). The comparison of model responses suggests that warming Atlantic increases moisture and further leads to wetting trend in DJF (Fig. 6a). During the boreal spring wet season, the model responses all show decreased moisture and enhanced divergence (Fig. 8d–f), in particular forced by Indian and Pacific Ocean, causing corresponding dry trend in AM (Fig. 6d–f).

Simulated changes of vertically integrated moisture flux convergence (Fig. 9) resemble the changes of moisture at 825 hPa (Fig. 8). There are significantly negative correlations between them in different SST forcing (pattern correlations in Additional file 1: Table.S2). Enhanced (reduced) moisture at low level is accompanied by strong convergence (divergence). In the boreal winter dry season, the tropical Atlantic forcing leads to a stronger moisture convergence, implying that more moisture is transported to the equatorial western Africa (Fig. 9a). Indian Ocean forcing induces the divergence (Fig. 9b) and Pacific forcing has no obvious signs (Fig. 9c). In the boreal spring wet season, the simulation results are consistent regarding more divergence (Fig. 9d–f), with a more widespread area driven by Indian Ocean forcing, which have a substantial impact on decreasing precipitation.

Overall, recent SST pattern causes changes of the Walker circulation and thus the moisture flux over the equatorial Africa, which increases precipitation in the boreal winter dry season and decreases precipitation in the boreal spring wet season. The variation of Atlantic and Indian Ocean forcing with season are more evident. Warming Atlantic drivers intensified Walker circulation

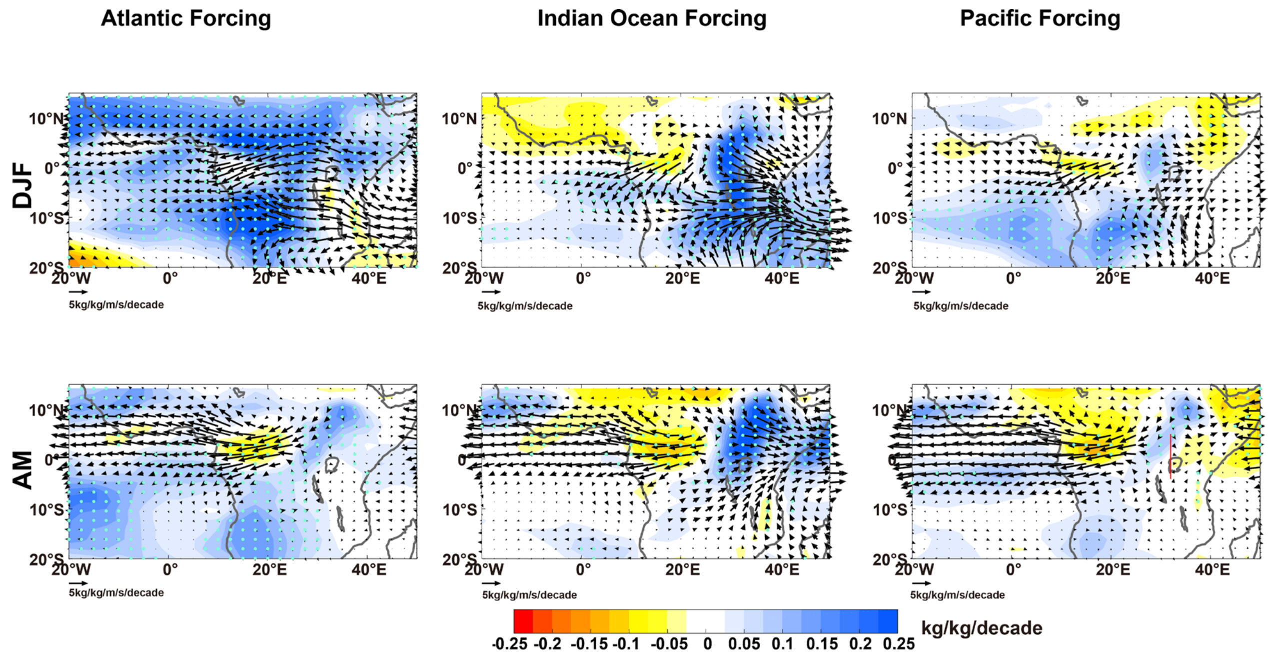

Fig. 8 Simulated seasonal change of moisture and moisture flux at 825 hPa in Atmospheric Models. Color mapping illustrates the special humidity change (increase, blue color; decreased, yellow color) and the vector illustrates the moisture flux change. Green dots indicate that special humidity change is significant at the 5% level. **a**–**c** show the change forced by the tropical Atlantic, Indian Ocean and Pacific during the boreal winter dry season (DJF). **d**–**f** same as **a**–**c** but for the boreal spring wet season (AM)

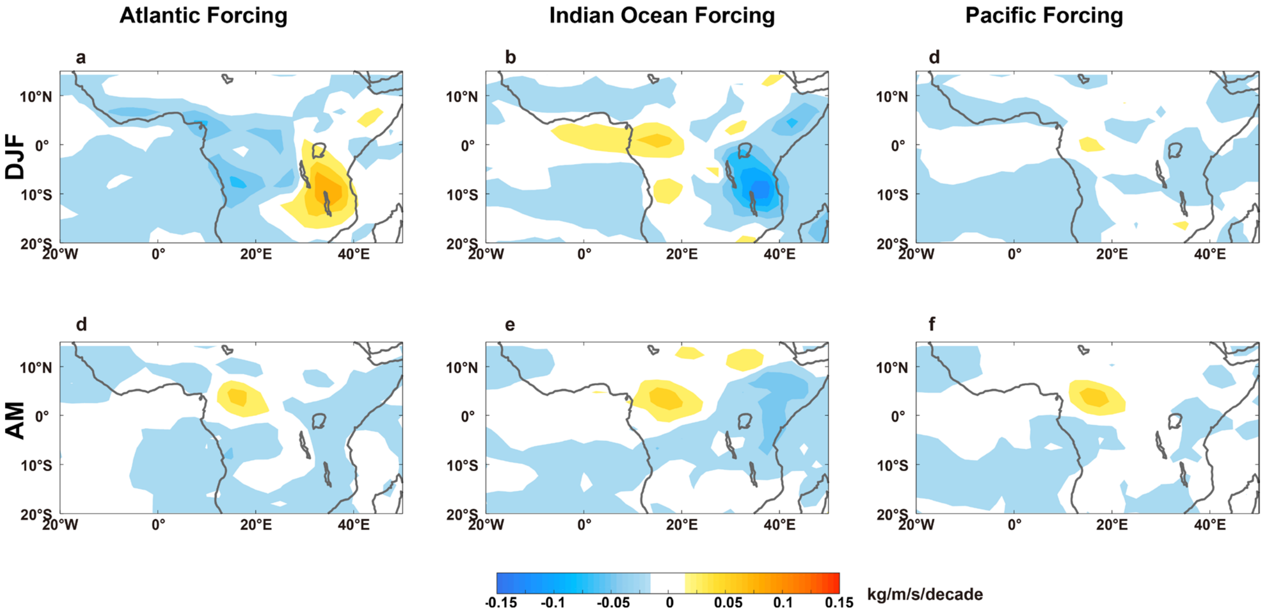

Fig. 9 Simulated seasonal change of vertically integrated moisture flux convergence in atmospheric models. Color mapping in **a**–**c** illustrates the convergence change (increase, blue color; decreased, yellow color) forced by the tropical Atlantic, Indian Ocean and Pacific during the boreal winter dry season (DJF). **d**–**f** same as **a**–**c** but for the boreal spring wet season (AM). The changes of convergence agree with specific humidity (Fig. 8)

over the Africa and thus lead to the increase of moisture convergence associated with deep convection and further strengthens precipitation in the boreal winter dry season. However, warming Indian Ocean weakens Walker circulation and the corresponding convergences in the boreal spring wet season, causing reductions in precipitation.

Conclusions and discussion

In this study, we examine the changes of precipitation over the African rainforest during the boreal winter dry season and boreal spring wet season from 1979 to 2015 by using observational precipitation datasets. We reveal that the seasonality of precipitation is dramatically weakened in observations, i.e., the wetting trend in the boreal winter dry seasons and the drying trend in the boreal spring wet season. The increased precipitation anomaly is ~ 0.13 mm/day/decade in DJF and decreased anomaly is ~ 0.21 mm/day/decade from 1979 to 2015 in AM, accounting for 14% (the precipitation changes from 1979 to 2015) of the climatology. As revealed in atmospheric models (CAM4), these changes are driven by tropical seasonal SST forcing, in particular the Atlantic and the Indian Ocean. Simulations show that the warming of the tropical Atlantic plays a key role in intensifying zonal circulation and moisture convergence over the equatorial Africa in boreal winter dry season, resulting in positive precipitation anomalies. However, warming Indian Ocean makes more contribution to weakening circulation and convection, leading to negative precipitation anomalies in boreal spring wet season.

However, the mechanism of seasonal precipitation change is mainly based on numerical simulations of a state-of-the-art atmospheric model. The relationship between SST and precipitation is extraordinarily complex in real world. In our study, observed intensified precipitation in the boreal winter dry season is only partly explained by Atlantic forcing. The model responses to Indian and Pacific Ocean forcing show negative precipitation anomalies in this dry season. Warming Atlantic plays an important role in strengthening moisture flux and warming Indian Ocean suppresses the convergence in DJF. The whole process tends to be nonlinear, and therefore the specific relationship between different SST and precipitation needs further study. In addition, for the other dry season (JJA) and wet season (SON), it is worthwhile to investigate whether the seasonality of precipitation weakens or strengthens and the roles of SST in the future.

The precipitation is of great importance to African rainforest and even the entire tropics. In recent decades, observed precipitation increased during the boreal winter dry season and decreased during the boreal spring wet season over the African rainforest. The opposite change of precipitation could cause a wetter dry season and a drier wet season, which may dramatically impact on the hydrological and ecosystem over the entire continent and around. Meanwhile, the deep convection associated with precipitation in different seasons, may have a further effect on the global circulation and potentially impact on the global climate system.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40562-021-00192-w.

Additional file 1: Figure S1. Same as Fig. 2, but for the precipitation trends from 1979 to 2019. Upper Panels (a, b) show the precipitation change during the boreal winter dry season (DJF) from GPCP and CMAP. Lower Panels (c, d) same as (a, b) but for the boreal spring wet season (AM). **Figure S2.** Same as Fig. 5, but for the climatological precipitation pattern in GPCP and CMAP. Upper Panels (a, b) show observed climatology in GPCP. Lower Panels (c, d) same as (a, b) but for CMAP. **Figure S3.** same as Fig. 1b, but for spatial averaged (the box in Fig. 1a, 7°E–32°E, 4°S–5°N) climatology of monthly precipitation in CAM model. **Figure S4.** The standard deviation of seasonal precipitation pattern in GPCP and CMAP. Left Panel (a, d) show the results in GPCP. Middle Panels (b, e) same as (a,d) but for CMAP. Right Panels (c, f) same as (a, d) but for models. **Figure S5.** Same as Fig. 6, but forced by tropical Ocean SST in atmospheric models. a is precipitation in DJF and b is precipitation in AM. **Table S1.** Pattern correlations of precipitation trends between observations and models. The region is 7°E–32°E, 4°S–5°N. **Table S2.** Pattern correlations between the trend of moisture at 825 hPa and the trend of divergence of vertically integrated moisture flux. The region is 7°E–32°E, 4°S–5°N.

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Authors' contributions

XL performed the model experiments. X-YW analyzed the datasets and wrote the manuscript. All authors contributed to the manuscript revision. All authors read and approved the final manuscript.

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Availability of data and materials

MODIS land cover map dataset (MCD12C1) is available at https://lpdaac.usgs.gov/get_data. Observational precipitation (GPCP and CMAP) is download from The NOAA Earth System Research Laboratory's Physical Sciences Division (https://www.esrl.noaa.gov/psd/data/gridded/tables/precipitation.html). Model datasets and materials analyzed in this study are accessible from the corresponding author under reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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