Regime shifts of the wet and dry seasons in the tropics under global warming

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Abstract

The main seasonal characteristics in the tropics include both spatial patterns and temporal parameters of onset, cessation, duration, and the number of wet and dry seasons. Previous studies showed that wet seasons shortened and dry seasons extended with global warming, but the changes in spatial distribution and the number of wet and dry seasons are still unclear. Here, we analyze the climatic characteristics of once wet and dry season a year (annual regime) and twice wet and dry seasons a year (biannual regime), and find that regimes of wet and dry seasons have changed from 1935 to 2014. Across the equator and the Tropic of Cancer and Capricorn, some regions where there used to be an annual regime have become a biannual regime; instead, other regions have shifted from a biannual regime into an annual regime. With seasonal regimes shifting, areas of the biannual regime have expanded at a rate of 31 000 km²/decade. Meanwhile, in annual regime regions, wet seasons have been shortened in 60.3% of regions, with an average of 7 d; the onset dates of wet seasons have been delayed in 64.8%, with an average of 6 d. Besides, wet seasons have become wetter in 51.1% of regions, and dry seasons have become drier in 59.9%. In biannual regime regions, the shortened wet seasons have occurred in 83.7% of regions, with an average shortening of 8 d, and precipitation has decreased in both wet and dry seasons. Moreover, the shorter wet seasons will amplify further by the end of the 21st century. The continuous seasonal changes will threaten agricultural, ecological security, and even human well-being.

1. Introduction

Driven by the seasonal migration of solar radiation and monsoons, one distinct feature of tropical seasonality is the transition between the dry and wet seasons [1]. The transitional periods between wet and dry seasons are vital to vegetation productivity [2–4], forest involvement [5–7], and disaster adaptation [8–10]. Therefore, concerns over changes in seasonal transitions [11, 12] are crucial in addressing regional climate, ecology, and hydrology problems [1, 13].

Recently, both model simulations and observed data have indicated that the total amount of water in the atmosphere increases at a rate of 7% per degree Kelvin of surface warming [14]. With this increasing atmospheric water, precipitation characteristics, which are closely linked with wet and dry seasons, have undergone significant variations [15, 16]. For example, enhanced precipitation intensities have increased the differences not only between wet and dry regions [17, 18] but also between wet and dry seasons [19]. The increased effective atmospheric heat capacity has postponed the onset dates of...
tropical seasons [20–22]. In addition, the combined changes in precipitation intensities and phases have led to more complex seasonal precipitation patterns over the tropics [16, 23] and have further increased uncertainties associated with seasonal transitions.

To date, significant changes in the onset, duration and precipitation characteristics of wet and dry seasons have been certified in many regions of the tropics. Tropical season postponements have been detected. For instance, Song et al [22] reported a seasonal delay of $4.1 \pm 1.1$ d from 1979 to 2019 over northern tropical lands. Moreover, the postponement of wet season onset dates has also been examined in South America [24, 25], western Africa [26] and East Africa [27]. Even worse, the wet-season onset dates are projected to be constantly delayed in the future. Particularly across South America, West Africa, the Sahel and southern Africa, wet seasons may be delayed by 2 weeks by the end of the 21st century [28, 29].

As the onset dates of the wet and dry seasons changed, so did their durations. Throughout India, generally decreased wet season durations have been found, with wet seasons having been shortened by 10–20 d per century [30]. This finding has been especially prominent for tropical rainforests. Since 1979, the dry season durations in the Amazon rainforest have increased [31], which has induced more frequent and more intense short-term droughts [32–35]. In the Congo rainforest, the earlier dry-season onset dates and later cessation dates resulted in increased dry season durations by 6.4–10.4 d per decade from 1988 to 2013 [6]. These longer dry seasons in rainforests can enhance water stress, affect the carbon cycle and alter the composition and structure of evergreen rainforests [6, 31, 36–38]. Moreover, shorter wet seasons can exacerbate water shortages [23, 39] and can even trigger humanitarian crises, such as the East African humanitarian crisis in 2011 [40].

Previous studies have focused on the timing of tropical seasons. However, little attention has been given to seasonal regimes. Generally, in most regions of the tropics, seasonal regimes can be categorized as annual regime (in which one wet season and one dry season occur per year) and biannual regime (in which two wet seasons and two dry seasons occur per year) [28]. With changing precipitation, the immutability of these seasonal regimes is affected. Some regions may experience an annual/biannual regime changing into a biannual/annual regime with climate change. These transitions between an annual regime and a biannual regime necessarily alter the local ecosystems [41–43] and affect local double-cropping systems [44]. In addition, although several studies have found shorter and later wet seasons and increased ranges of precipitation between the wet and dry seasons based on regional precipitation data [19, 21, 30], there remains a dearth of research on the evolution of wet and dry seasons in the whole tropics.

Consequently, in this study, we try to determine how seasonal regimes and wet and dry seasons change with climate warming. Firstly, we investigate changes in seasonal regimes that occurred during 1935–2014. Then, we study the changes in the duration, onset and cessation of wet and dry seasons by using reanalysis and future climate change scenario datasets (Phase 6 of the Coupled Model Intercomparison Project (CMIP6)). At the same time, we analyze the precipitation variability characteristics during different seasons to reveal the variations of wet and dry seasons in the tropics.

2. Methods and data

2.1. Definition of tropical seasons

The onset and cessation dates of the wet and dry seasons are calculated by using the cumulative rainfall anomaly methodology of Dunning et al [45]. Since this method does not require that a unified threshold be set in advance, it is applied herein to identify the onset and cessation dates of wet and dry seasons throughout the tropics. The method has three stages as follows.

Firstly, harmonic analysis is applied to the whole time series to categorize the seasonal regime at each grid point. The seasonal regime at each grid point is then categorized as an annual regime/biannual regime when the ratio of the amplitude of the second harmonic to the amplitude of the first harmonic is less/greater than 1.0. Here, we describe a region that experiences one wet and dry season per year as having an annual regime and a region that experiences two wet and dry seasons per year as having a biannual regime. Moreover, the biannual wet seasons are classified as ‘long rain’ (boreal spring wet season) or ‘short rain’ seasons.

Secondly, the onset and cessation of climatological wet seasons are determined by identifying the minima and maxima of the climatological cumulative daily rainfall anomaly. The climatological cumulative daily rainfall anomaly on day $d$, denoted as $C_{(d)}$, is calculated using the following formula:

$$C_{(d)} = \sum_{i=1}^{d} (P_i - \bar{P})$$  \hfill (1)$$

where $P_i$ represents the climatological mean rainfall for each day of the calendar year, where $i$ ranges from 1 January to day $d$; $\bar{P}$ is the climatological daily mean rainfall; and $C_{(d)}$ is calculated for each day from 1 January to 31 December. Obviously, when the daily precipitation is above the climatological mean daily rainfall, the cumulative daily precipitation anomaly increases, and vice versa. Therefore, the onset and cessation dates of wet seasons can be defined by finding the minima and maxima $C_{(d)}$ values, respectively.

Finally, according to the climatic wet season information, the onset and cessation dates of the dry
and wet seasons are calculated for each year through the cumulative precipitation anomaly methodology. The detailed steps of this methodology are available in the literature [28, 45].

To analyze changes in wet and dry seasons, we compare the variation characteristics in durations of wet seasons under 10 year periods and 20 year periods. We find that results are more stable under 20 year periods (figures S1 and S2). Meanwhile, in some regions, the season shows 20 year cycles of wet and dry phases, such as in eastern Africa [46]. Therefore, the method is applied separately every 20 years (1935–1954, 1955–1974, 1975–1994, 1995–2014).

2.2. Data
The daily precipitation data in this study include reanalysis and model simulation outputs. The reanalysis data are obtained from the National Oceanic and Atmospheric Administration–Cooperative Institute for Research in Environmental Sciences–Department of Energy (NOAA-CIRES-DOE) 20th Century Reanalysis V3 (20CRv3) from 1836 to 2015 at a 1° × 1° resolution. We also use the Tropical Rainfall Measuring Mission (TRMM) Multi-Satellite Precipitation Analysis Rainfall Estimate Product 3B42 Version 7 (TRMM 3B42-V7), with a 0.25° grid resolution and covering 1998–2019, Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) global daily precipitation data from 1981 to 2022, with a 0.05° grid resolution [47], the Global Precipitation Climatology Centre (GPCC) Full Data Daily Product Version 2020 from 1982 to 2020 with a 1° grid resolution [48], and GPCC Full Data Monthly Product Version 2022 from 1891 to 2020 with a 1° grid resolution to verify the reliability of 20CRv3. We find that 20CRv3 can well characterize the variations of annual precipitation and seasonal precipitation from 1985 to 2014 between 30° N and 30° S (figures S3–S5 and table S2). Besides, the variations of annual and monthly precipitation in the tropics are described well by 20CRv3 from 1935 to 2014 (figures S6–S8). Since TRMM 3B42-V7, CHIRPS and GPCC are available for a short time period and GPCC Full Data Monthly Product cannot be used to calculate wet and dry season (by the cumulative rainfall anomaly methodology), only the results of 20CRv3 with a longer time period are presented in this paper.

The model simulation outputs are obtained from CMIP6, detailed in table S1. These include coupled simulations for the past (1935–2014 historical experiment) and projections made thereafter from 2015 to 2094 (medium- (shared socioeconomic pathways (SSPs) 2-4.5) and high-emission (SSP5-8.5) scenarios). Those models can not only better simulate both the spatial distribution and magnitude of annual precipitation but also can reproduce the shortened and delayed onset dates of wet seasons from historical experiments (table S1, figures S16–S18).

3. Results

3.1. Regime shifts of the tropical wet and dry seasons
The seasonal regimes across the tropics can be categorized as annual regime (one wet and dry season per year) and biannual regime (two wet and dry seasons per year). Visually, most of the tropics are identified as annual regime regions (figures 1(a) and S9). Biannual regime regions are relatively small and are mainly distributed along the equator and near the Tropics of Cancer and Capricorn. Near the equator, biannual regime regions are concentrated in the Congo Rainforest, the Horn of Africa, and parts of Columbia and Indonesia. Near the Tropic of Cancer and Capricorn, biannual regime regions are located in the southern United States, the Sahara Desert, the Arabian Peninsula, Pakistan and Australia. However, seasonal regimes are not always immutable (figure S10). Compared to 1935–1954, from 1995–2014, more regions have changed from an annual regime to a biannual regime, such as the Sahara Desert, Congo rainforest, Horn of Africa, Arabian Peninsula and Indonesia. Conversely, fewer regions have changed from a biannual regime to an annual regime, such as Mexico, northern South America, the northern coast of Guinea and the Arabian Sea, and mid-Australia (figure 1(b)). With more regions shifting from an annual regime to a biannual regime, biannual regime regions have expanded while annual regime regions have reduced. From 1935–1954 to 1995–2014 the proportion of biannual regime regions has increased from 10.1% to 11.1%; while the proportion of annual regime regions has reduced from 89.9% to 88.9% (figure S11). The biannual regime region has expanded as a rate of 31 000 km²/decade.

Furthermore, we select eight typical regions, where seasonal regimes have changed, and analyze the regional precipitation variations. In regions I–IV, the annual regime has changed into the biannual regime. In some regions, increasing seasonal precipitation turns one wet season into two wet seasons. Conversely, in other regions, the decreasing seasonal precipitation interrupts the wet season into two wet seasons, especially along the equator. For instance, the region I, which is located in northeastern Mexico (figure 1(b)), used to experience one wet season from December to April (figure 1(I)) from 1935 to 1954. However, with the increased rainfall from July to September, the region I have converted into two distinct wet seasons: November–April and July–September after 1955 (figures 1(I) and S10(b)). Similarly, the increasing seasonal precipitation also changed the annual regime into the biannual regime in regions III and IV (figures 1(III) and (IV)). Region II is located in the Congo rainforest (figure 1(b)), with one wet season per year from 1935 to 1954. But the
Figure 1. (a) Spatial patterns of the annual/biannual regime from 1995 to 2014. Orange/yellow grid points indicate the biannual/annual regime. (b) Changes in the annual/biannual regime from 1995–2014 compared to 1935–1954. The black dots represent regions I–VIII. Blue colors indicate regions where number of wet and dry seasons decreased (a biannual regime has changed into an annual regime), while red colors are opposite. (I) Climatic mean precipitation in the region I located in Mexico (represented by the black dot in (b)). The black and orange lines are the climatological cumulative daily rainfall anomalies from 1935 to 1954 and from 1995 to 2014, respectively. (II)–(VIII) As in (I), but for region II–VIII (represented by the black dot in (b)).

Decreasing rainfall from June to August interrupted the wet season (March–November) into two wet seasons (March–June and August–November) from 1995 to 2014 (figure 1(II)).

In contrast, region V–VIII experienced the biannual regime changing into the annual regime. In some regions, decreasing precipitation shifts the biannual regime into the annual regime. For example, located in Pakistan (figure 1(b)), region VII used to have two wet seasons each year: February–April and June–September from 1935 to 1954. However, from 1995 to 2014, a significant reduction in precipitation from January to March has resulted in the disappearance of the concurrent wet season. Likewise, the decreasing seasonal precipitation also has changed the biannual regime into the annual regime in regions V and VIII (figures 1(V) and (VIII)). Meanwhile, the increasing precipitation can combine two distinct wet seasons into one wet season. Figure 1(VI) shows that the increased precipitation from July to September changed two wet seasons (March–July and September–November) into one wet season (April–November) from 1995 to 2014.

These changes in the annual/biannual regime might alter the local ecosystems and pose threats to the normal lives of local peoples [49]. For instance, in Pakistan, the areas of the biannual regime have shrunk (figures S12(a) and (b)).
the biannual regime change into the annual regime, more precipitation is concentrated in the single wet season (figure S12(c)). This more concentrated rainfall enhances the frequency and intensity of extreme events and can even induce survival crises [50]. Besides, when seasonal regimes have changed, the new precipitation patterns might not be compatible with local double-cropping systems [44], resulting in crop failures.

3.2. Changes in wet and dry seasons under the annual regime

To gain a comprehensive understanding of tropical seasons, next, we discuss the observed changes in the durations of tropical seasons. We find that, compared to 1935–1954, wet seasons shortened in 60.3% of annual regime regions by an average of 7 d (figure S13), from 1995–2014. In northern and western South America, north and south Africa, Southeast Asia (figure 2(a)), wet seasons have experienced significant shortening, with an average of 15 d. In particular, the wet seasons have shortened across 80% of the African continent. In contrast, regions, where the wet seasons have been prolonged, are relatively small and are mainly located in Brazil, Paraguay, Argentina, Ethiopia, Tanzania and eastern China, with an average prolonging of 6 d (figure 2(a)).

In addition, figures 2(b) and (c) show the recorded shifts in the wet season onset and cessation dates. From 1935–1954 to 1995–2014, the onset dates of the wet seasons are delayed in 64.8% of annual regime regions by an average of 6 d (figures 2(b) and S13). Especially over Mexico, the Andes, the Sahel, Angola to Madagascar and southeast Asia, the onset dates of the wet season are delayed by approximately 18 d. Furthermore, according to figures 2(a) and (b), good spatial consistencies can be found between the wet season durations and onset dates, meaning that the shortened wet seasons are mainly caused by the postponed onset dates. Moreover, the cessation dates

![Figure 2. Changes in the (a) duration, (b) onset, and (c) cessation of the annual wet season from 1995–2014 compared to 1935–1954. Blue colors in (a) indicate the duration getting longer while red colors indicate duration getting shorter. Red colors in (b) and (c) indicate the onset/cessation getting later while blue colors indicate onset/cessation getting earlier. Dotted grids indicate the changes significantly different between the period of 1935–1954 and the period of 1995–2014 (Mann–Whitney U test, 5% significance level).]
of the wet season have been apparently postponed across Mexico, northern Brazil, southern Sudan and parts of China, with an average of 9 d (figure 2(c)). While, cessation dates of the wet season dates have been advanced in Colombia, south-central Brazil, the northern coast of the Gulf of Guinea, Tanzania, Madagascar and northeastern Australia, with an average of 8 d.

As the durations, onsets and cessations of wet and dry seasons change, so does precipitation. Wet seasons have become wetter, with 51.1% of annual regime regions experiencing increased precipitation, including North America, Central South America, Southern Africa, Northern India, western China, and Northwestern Australia (figure S14(a)). According to our statistics (figure S15), during the wet season, extreme precipitation is increasing at a rate of 8.5 mm/10 years in 86.3% of annual regime regions. The increased volume and intensity of wet season precipitation may result in more frequent and severe floods [51, 52]. Meanwhile, dry seasons have become drier in 59.9% of annual regime regions. In northern South America, Africa, Southeast Asia and Australia (figure S14(b)), this decreased dry-season precipitation can lead to lowered water availabilities [53] and promote severe fire seasons [54]. In addition, as dry seasons coincide with increased rotavirus transmission [55] and wet seasons coincide with outbreaks of malaria and dengue fever [56, 57], these precipitation changes observed in the wet and dry seasons can lead to disease outbreaks.

3.3. Changes in wet and dry seasons under the biannual regime

Among biannual regime regions, changes in durations of wet seasons are concentrated in central America (figure 3(a)), Australia and Southeast Asia (figure 3(b)), and equatorial Africa (figure 3(c)). Wet seasons have shortened in 83.7% of biannual regime regions by an average of 8 d and are mainly distributed in equatorial Africa. Therefore, we select the Congo rainforest (9° E–36° E, 2° S–5° N) and the Horn of Africa (38° E–50° E, 1° S–13° N) to investigate the onset and cessation dates of wet and dry seasons by analyzing the regional average precipitation time series. According to figure 3(d), the Congo rainforest has experienced a long-term reduction in precipitation; this finding is the same as the conclusion of Asefi-Najafabadi et al [58] and Cook et al [59]. This reduced precipitation postpones the long-rain onset dates and leads to shortened wet seasons. In the long run, the continued drought and postponement of the wet season may affect the structure of rainforests [5], even turning evergreen forests into deciduous forests. Similarly, in the Horn of Africa figure 3(e), the reduction in precipitation has induced wet season shortening from 1995–2014, compared to 1935–1954. Given that precipitation affects irrigation and agriculture, these shorter, drier wet seasons may plunge the Horn of Africa into severe drought, even triggering humanitarian crises [8].

3.4. Projected changes in wet and dry seasons in the future

According to reanalysis data, the wet seasons in the tropics are suffering from changes in temporal rhythms and their spatial patterns under climate change. To predict epochal changes in tropical seasons, we first evaluate and select 7 CMIP6 models, as shown in table S1, that reproduce wet-season variability through historical experiments well (figures S16–S18). Then, we use the outputs of these 7 CMIP6 models to project changes in wet and dry seasons under future climate scenarios. The following feature descriptions are mainly based on the SSP5-8.5 scenario. The changes derived from the CMIP6 models under SSP2-4.5 (figures S19–S21) are generally of the same sign as those shown in figures 4–5 and S22 but of lower magnitude.

Based on the CMIP6 projections, although biannual regime regions will still be distributed along the equator and near the Tropics of Cancer and Capricorn (from the CMIP6 models figures. S23–S24), the spatial pattern will change by the end of the 21st century (figure 4). Compared to 1995–2014, from 2075–2094, the annual regime will change into the biannual regime across Mexico, northern of Congo rainforest, the southern Sahara Desert and Arabian Peninsula; while the biannual regime will change into the annual regime across South America, the northern Sahara Desert, southern of Congo rainforest, Indonesia, and mid-Australia. Besides, at the equator, biannual regime regions will shift northward. Between 0° and 10° S, the biannual regime will change into the annual regime. Conversely, between 0° and 10° N, the annual regime will change into the biannual regime. It should be noted that the number of models in figure 4 is just about three out of the seven selected models, as CMIP6 projections of changing seasonal regimes vary widely across climate models [60].

Meanwhile, the shortening and delaying of wet seasons are expected to amplify in the future (figure 5). In annual regime regions, from 1995–2014 to 2075–2094, the wet season is expected to shorten by an average of 8 d in 61.1% of annual regime regions, and the wet season onset dates are predicted to be delayed by an average of 7 d in 76.3% of regions (figure S13). At the end of the 21st century, the contractions and postponements of wet seasons will intensify. Compared to the conclusions of reanalysis data from 1935–2014, the regions of contracted wet seasons are expected to increase by 0.8% during the 21st century, while the regions of delayed wet seasons
may increase by 11.5%. In the biannual regime, wet seasons will shrink by an average of 7 d from 1995–2014 to 2075–2094. In northern South America, the Congo rainforest, the Horn of Africa and Australia (figure S22(a)), wet seasons will undergo significant shortening by an average of 10 d.
Figure 5. Median change in (a) duration, (b) onset and (c) cessation of the annual wet season, in 7 CMIP6 simulations from 1995–2014 (historical simulation) to 2075–2094 (SSP5-8.5 scenario). Blue colors in (a) indicate the duration getting longer while red colors indicate duration getting shorter. Red colors in (b) and (c) indicate the onset/cessation getting later while blue colors indicate onset/cessation getting earlier. Dots indicate more than 50% of the models show a statistically significant change (Mann–Whitney U test, 5% significance level).

4. Conclusions

By analyzing the spatial distributions of seasonal regimes, we find that regimes of wet and dry seasons have changed with global warming. Along the equator and near the Tropics of Cancer and Capricorn, more regions have experienced a conversion from an annual regime into a biannual regime; while fewer regions have shifted from a biannual regime into an annual regime. From 1935 to 2014, with more regions shifting from an annual regime into a biannual regime, biannual regime regions have expanded. Besides, most tropical regions have experienced shorter and later wet seasons. In annual regime regions, wet seasons have shortened in 60.3% of regions by an average of 7 d, and the onset dates of wet seasons have been delayed in 64.8% of regions by an average of 6 d. As the durations of wet and dry seasons change, so does precipitation. Wet seasons have become wetter in 51.1% of regions; while dry seasons have become drier in 59.9% of regions. In biannual regime regions, as all seasons’ precipitation has decreased, shortened wet seasons have occurred in 83.7% of regions, with an average shortening of 8 d. Moreover, the CMIP6 projection shows that the changes in seasonal regimes will continue along the equator and near the Tropics of Cancer and Capricorn from 2015 to 2094. Meanwhile, wet seasons are expected to shorten further, by an estimated average of 8 d in 61.1% of annual regime regions, while the onset dates are predicted to be delayed further, by an estimated average of 7 d in 76.3% of annual regime regions. Similarly, under the biannual regime, durations of the wet season are expected to further shrink by an average of 7 d.

On the hemispherical scale, Song et al [22] contributed delayed seasonal precipitation to increasing greenhouse gases and decreasing anthropogenic aerosols. In biannual regime regions, Cook et al pointed out that [59] poleward shifts of the continental
thermal lows weakened the convergence of the Congo Basin, which reduced wet seasons’ precipitation. Gudoshava et al [61] also found that in eastern Africa early onset dates of ‘short rains’ were associated with warmer sea surface temperatures in the western Indian Ocean. Meanwhile, in annual regime regions, Fu et al [31] mentioned the delayed onset dates of wet seasons may be caused by poleward shift of the subtropical jet and increased local convective inhibition energy over southern Amazonia. However, little attention has been given to the regime shifts of the wet and dry seasons from the perspective of the whole tropics. Since the changes in precipitation patterns might alter the local agricultural, ecosystem, and even threaten human well-being, the relevant mechanisms of regime shift in the wet and dry seasons need to be explored in the future.

Data availability statement

The data that support the findings of this study are openly available. The TRMM 3B42-V7 data are available for download (https://disc2.gesdisc.eosdis.nasa.gov/opendap/TRMM_L3/TRMM_3B42_Daily.7/). The CHIRPS data are available for download (www.chc.ucsb.edu/data/chirps). The daily and monthly GPCC data are available for download (https://opendata.dwd.de/climate_environment/GPCC/html/download_gate.html). The 20CRv3 data are available for download (https://psl.noaa.gov/data/grid/zed/data.20thC_ReanV3.html). The CMIP6 outputs are downloaded from (https://esgnode.lnl.gov/search/cmip6/).

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] Bombardi R J, Moron V and Goodnight J S 2020 Detection, variability, and predictability of monsoon onset and withdrawal dates: a review Int. J. Climatol. 40 641–67
[2] Cooper P J, Dines J, Rao K, Shapiro B, Shiferaw B and Twomlow S 2008 Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: an essential first step in adapting to future climate change Agric. Ecosyst. Environ. 126 24–35
[3] Vizy E K, Cook K H, Chimphamba J and McCurker B 2015 Projected changes in Malawi's growing season Clim. Dyn. 45 1673–98
[4] Zhang M, Abrahao G and Thompson S 2021 Sensitivity of soybean planting date to wet season onset in Mato Grosso, Brazil, and implications under climate change Clim. Change 168 1–28
[5] Fauset S, Baker T R, Lewis S L, Feldpausch T R, Affum-Baffoe K, Foli E G, Hamer K C and Swaine M D 2012 Drought-induced shifts in the floristic and functional composition of tropical forests in Ghana Ecol. Lett. 15 1120–9
[6] Jiang Y, Zhou L, Tucker C J, Raghavendra A, Hua W, Liu Y Y and Joiner J 2019 Widespread increase of boreal summer dry season length over the Congo rainforest Nat. Clim. Change 9 617–22
[7] Wright S J and Van Schaik C P 1994 Light and the phenology of tropical trees Am. Nat. 143 192–9
[8] Lott F C, Christidis N and Stott P A 2013 Can the 2011 East African drought be attributed to human-induced climate change? Geophys. Res. Lett. 40 1177–81
[9] Tanser F C, Sharp B and Le Sueur D 2003 Potential effect of climate change on malaria transmission in Africa Lancet 362 1792–8
[10] Tierney J E, Ummenhofer C C and Demenocal P B 2015 Past and future rainfall in the Horn of Africa Sci. Adv. 1 e1500682
[11] Moron V and Robertson A W 2020 Tropical rainfall subseasonal-to-seasonal predictability types npj Clim. Atmos. Sci. 3 4
[12] Washington R, Harrison M, Conway D, Black E, Challinor A, Grimes D, Jones R, Morse A, Kay G and Todd M 2006 African climate change: taking the shorter route Bull. Am. Meteorol. Soc. 87 1355–66
[13] Misra V and Bhardwaj A 2020 The impact of varying seasonal length of the rainy seasons of India on its telecommunications with tropical sea surface temperatures Atmos. Sci. Lett. 21 e059
[14] Wentz F J, Riicciardulli L, Hibburn K and Mears C 2007 How much more rain will global warming bring? Science 317 233–5
[15] Deng S, Sheng C, Yang N, Song L and Huang Q 2020 Anthropogenic forcing enhances rainfall seasonality in global land monsoon regions Environ. Res. Lett. 15 104057
[16] Feng X, Porporato A and Rodriguez-Iturbe I 2013 Changes in rainfall seasonality in the tropics Nat. Clim. Change 3 811–5
[17] Schurer A P, Ballinger A P, Friedman A R and Hegerl G C 2020 Human influence strengthens the contrast between tropical wet and dry regions Environ. Res. Lett. 15 104026
[18] Liu C and Allan R P 2015 Observed and simulated precipitation responses in wet and dry regions 1850–2100 Environ. Res. Lett. 8 034002
[19] Chou C, Chiang I C H, Lan C-W, Chung C-H, Liao Y-C and Lee C-J 2013 Increase in the range between wet and dry season precipitation Nat. Geosci. 6 263–7
[20] Biasutti M and Solov A H 2009 Delayed Sahel rainfall and global seasonal cycle in a warmer climate Geophys. Res. Lett. 36 123707

[21] Song F, Lu J, Leung L R and Liu F 2020 Contrasting phase changes of precipitation annual cycle between land and ocean under global warming Geophys. Res. Lett. 47 e2020GL090327

[22] Song F, Leung L R, Lu J, Dong L, Zhou W, Harrop B and Qian Y 2021 Emergence of seasonal delay of tropical rainfall during 1979–2019 Nat. Clim. Change 11 605–12

[23] Pascale S, Lucarini V, Feng X and Portoraro A 2015 Analysis of rainfall seasonality from observations and climate models Clim. Dyn. 44 3281–301

[24] Arias P A, Fu B, Vera C and Rojas M 2015 A correlated shortening of the Northern and South American monsoon seasons in the past few decades Clim. Dyn. 45 3183–203

[25] Carvalho L M, Jones C, Silva A E, Liebmann B and Silva Dias P L 2011 The South American monsoon system and the 1970s climate transition Int. J. Climatol. 31 1248–56

[26] Sylla M B, Giorgi F, Pal J S, Gibba P, Kebe I and Nikiema M 2015 Projected changes in the annual cycle of high-intensity precipitation events over West Africa for the late twenty-first century J. Clim. 28 6475–88

[27] Seregina I S, Fink A H, van der Linden R, Elagib N A and Pinto J G 2019 A new and flexible rainy season definition: validation for the Greater Horn of Africa and application to rainfall trends Int. J. Climatol. 39 989–1012

[28] Dunning C M, Black E and Allan R P 2018 Later wet seasons with more intense rainfall over Africa under future climate change J. Clim. 31 9719–38

[29] Wainwright C M, Allan R P and Black E 2021 Future changes in wet and dry season characteristics in CMIP5 and CMIP6 simulations J. Hydrometeorol. 22 2339–57

[30] Sahany S, Mishra S K, Pathak R and Rajagopalan B 2018 Spatiotemporal variability of seasonality of rainfall over India Geophys. Res. Lett. 45 7140–70

[31] Fu R et al 2013 Increased dry-season length over southern Amazonia in recent decades and its implication for future climate projection Proc. Natl Acad. Sci. USA 110 18110–5

[32] Erfanian A, Wang G and Fomenko L 2017 Unprecedented drought over tropical South America in 2016: significantly under-predicted by tropical SST Sci. Rep. 7 3811

[33] Marengo J A, Nobre C A, Tomassella I, Oyama M D, de Oliveira G S, De Oliveira R, Camargo H, Alves L M and Brown I F 2008 The drought of Amazonia in 2005 J. Clim. 21 495–516

[34] Marengo J A, Tomassella J, Alves L M, Soares W R and Rodrigues D A 2011 The drought of 2010 in the context of historical droughts in the Amazon region Geophys. Res. Lett. 38 L11203

[35] Wainwright C M, Allan R P and Black E 2022 Consistent trends in dry spell length in recent observations and future projections Geophys. Res. Lett. 49 e2021GL097231

[36] Cox P M, Betts R A, Jones C D, Spill A S and Tottell D J I 2000 Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model Nature 408 184–7

[37] Duffy P B, Brando P, Asner G P and Field C B 2015 Projections of future meteorological drought and wet periods in the Amazon Proc. Natl Acad. Sci. USA 112 13172–7

[38] Phillips O L et al 2009 Drought sensitivity of the Amazon rainforest Science 323 1344–7

[39] Cashman A, Nurse L and John C 2010 Climate change in the Caribbean: the water management implications J. Environ. Dev. 19 42–67

[40] Lyon B and DeWitt D G 2012 A recent and abrupt decline in the East African long rains Geophys. Res. Lett. 39 L02702

[41] Fekadu M B, Agembe S, Kiptum C K and Mingist M 2022 Impacts of anthropogenic activities on the benthic macroinvertebrate assemblages during the wet season in Kipsinende River, Kenya Turkish J. Fish. Aquat. Sci. 22 TRJFAS18410

[42] Warfe D M et al 2011 The ‘wet–dry’in the wet–dry tropics drives river ecosystem structure and processes in northern Australia Freshw. Biol. 56 2169–95

[43] Yoshifuji N, Kumagai T O, Tanaka K, Tanaka N, Komatsu H, Suzuki M and Tantasirin C 2006 Inter-annual variation in growing season length of a tropical seasonal forest in northern Thailand For. Ecol. Manage. 229 333–45

[44] Arvor D, Dubreuil V, Ronchail J, Simões M and Funatsu B M 2014 Spatial patterns of rainfall regimes related to levels of double cropping agriculture systems in Mato Grosso (Brazil) Int. J. Climatol. 34 2622–33

[45] Dunning C M, Black E C and Allan R P 2016 The onset and cessation of seasonal rainfall over Africa J. Geophys. Res. Atmos. 121 11,405–24

[46] Omonti P, Avangie L, Ogollo L, Okosa R and Forozan E 2012 Decadal rainfall variability modes in observed rainfall records over East Africa and their relations to historical sea surface temperature changes J. Hydrol. 464 140–56

[47] Funk C et al 2015 The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes Sci. Data 2 150066

[48] Schamk K, Zies M, Becker A, Finger P, Meyer-Christoffer A, Schneider U, Schröder M and Stender P 2014 Global gridded precipitation over land: a description of the new GPCP first guess daily product Earth Syst. Sci. Data 6 49–60

[49] Kirby M, Maimuddin M, Khaliq T and Cheema M 2017 Agricultural production, water use and food availability in Pakistan: historical trends, and projections to 2050 Agric. Water Manage. 179 34–46

[50] Ghani A and Muhammad A 2017 Climate change impacts for food security; Pakistan perspective Agric. Res. Tech. 7 535716

[51] Barichivich J, Gloor E, Peñin P, Brienon R J, Schöngart J, Espinoza J C and Pattynak C K 2018 Recent intensification of Amazon flooding extremes driven by strengthened Walker circulation Sci. Adv. 4 eaa7875

[52] Trenberth K E, Dai A, Rasmussen R M and Parsons D B 2003 The changing character of precipitation Bull. Am. Meteorol. Soc. 84 1265–18

[53] Kumar S, Lawrence D M, Dirmeyer P A and Sheffield J 2014 Less reliable water availability in the 21st century climate projections Earth’s Future 2 152–60

[54] Brando P M et al 2014 Abrupt increases in Amazonian tree mortality due to drought–fire interactions Proc. Natl Acad. Sci. USA 111 6347–52

[55] Levy K, Hubbard A E and Eisenberg J N 2009 Seasonality of rotavirus disease in the tropics: a systematic review and meta-analysis Int. J. Epidemiol. 38 1487–96

[56] Bomblies A 2012 Modeling the role of rainfall patterns in seasonal malaria transmission Clim. Change 112 673–85

[57] Chumpu R, Khamseman R and Natte C 2019 The association between dengue incidences and provincial-level weather variables in Thailand from 2001 to 2014 PLoS One 14 e0226945

[58] Asefi-Najafabady S and Saatchti S 2013 Response of African humid tropical forests to recent rainfall anomalies Phil. Trans. R. Soc. B 368 20120306

[59] Cook K H, Liu Y and Vizy E K 2020 Congo basin drying associated with poleward shifts of the African thermal lows Clim. Dyn. 54 863–83

[60] Thackeray C W, Hall A, Norris J and Chen D 2022 Constraining the increased frequency of global precipitation extremes under warming Nat. Clim. Change 12 441–8

[61] Gudoshava M, Wainwright C, Hiron S, Endris H S, Segele Z T, Woolnough S, Athen A Z and Artan Z 2022 Atmospheric and oceanic conditions associated with early and late onset for eastern Africa short rains Int. J. Climatol. 1–17