Anthropogenic forcing enhances rainfall seasonality in global land monsoon regions

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Abstract
Understanding how humanity’s influence on the climate affects rainfall seasonality around the world is immensely important for agriculture production, ecology protection, and freshwater resource management. In this study, we qualitatively and quantitatively analyzed the potential influence of anthropogenic forcing on rainfall seasonality in global land monsoon (GM) regions using the Coupled Model Intercomparison Project Phase 5 (CMIP5) general circulation models. We discovered that anthropogenic forcing enhances rainfall seasonality over many parts of GM regions, and was evident in the South Asian and the most parts of the South American and the South African monsoon regions. Anthropogenic forcing partially but clearly contributed to the increasing trend of rainfall seasonality over many parts of GM regions from 1960 to 2012. Moreover, anthropogenic forcing also increased the probability of more pronounced rainfall seasonality in almost all GM regions. The results provide valuable information for agriculture, ecology, and freshwater resource management under climate warming induced by anthropogenic forcing.

1. Introduction
Rainfall seasonality and drought duration are important factors for monsoonal rainfall regimes. In monsoon regions, reduced rainfall in combination with shortened wet seasons may have the potential to cause prolonged drought, and thereby directly impacting the agricultural economy in agricultural regions (Pascale et al 2015). In addition, approximately 62% of the world’s population lives in monsoon regions (Zhang et al 2018), and changes in rainfall seasonality create huge challenges for the resource management of sustainable fresh drinking water. Climate seasonality is particularly important because it influences ecosystem diversity (Gitau 2016). Many ecosystems, such as the Caatinga ecosystem of Brazil (Souza et al 2016), tropical dry ecosystems (Rohr et al 2013), herbaceous Mediterranean vegetation (Clary 2008), tropical monsoon vegetation (Dubois et al 2014), and the malaria ecosystem (Briet et al 2008), are all extremely sensitive to changes in rainfall seasonality. Rainfall seasonality is closely associated with agriculture, ecology, and freshwater resource management. Thus, it is both urgent and important to understand changes in rainfall seasonality under global warming.

Rainfall seasonality is a complex concept that consists of many components, including the magnitude, timing, and duration of the wet and dry seasons (Livada and Asimakopoulos 2005). Rainfall metrics,
including relative entropy (RE), the dimensionless seasonality index (DSI), and the timing and duration of wet seasons, have recently been introduced by Feng et al. (2013) based on a probabilistic interpretation of rainfall fractions, which are the diversities between the actual monthly fractions of precipitation and uniform monthly precipitation sequence for each given year, and the concept of RE borrowed from information theory.

Based on observed rainfall data, rainfall seasonality has changed over the past decades, and will continue to change in the future across many parts of the world according to global or regional climate models (Sahany et al. 2018). Results using the metrics developed by Feng et al. (2013) have revealed that the interannual variability of rainfall seasonality has increased over many parts of the dry tropics over the past century, implying increasing uncertainty in the intensity, arrival, and duration of wet season. Rainfall seasonality and total annual rainfall both exhibited significant decreasing trends over parts of central India, the Indo-Gangetic Plains, and parts of the Western Ghats, but increased in the remaining sections of India from 1901 to 2013 (Sahany et al. 2018). In Southeast China, rainfall seasonality also increased from 1961 to 2012, which can be attributed to changes in either the annual rainfall, or the timing or duration of the wet season (Deng et al. 2019). Moreover, the timing of the wet season is expected to delay in the hydrological year by the end of the twenty-first century, particularly after 2050, based on the Coupled Model Intercomparison Project Phase 5 (CMIP5) general circulation models (GCMs). This trend is projected to be particularly pronounced over northern Africa, southern Africa and western Mexico (Pascale et al. 2016). The MIT Regional Climate Model (MRCM) simulation ensemble also projects a significant decrease in rainfall over the western Maritime Continent during the inter-monsoon periods (Kang et al. 2019). The possible physical mechanisms behind rainfall seasonality changes are quite complex, however, and are thus difficult to qualitatively and quantitatively analyze.

Global warming increases the frequency and intensity of extreme rainfall events, and also changes other properties of rainfall patterns such as rainfall seasonality (Kumar 2013). With both thermodynamic and dynamic mechanisms at play under anthropogenic forcing, climate warming induced by anthropogenic forcing is expected to alter the precipitation in global land monsoon (GM) regions (IPCC 2013, Zhou et al. 2020). Actually, anthropogenic forcing have been attributed to changes in the Asian (Wang et al. 2019), the West African (Undorf et al. 2018), the South Asian (Singh et al. 2019), and western North Pacific monsoon precipitation (Takahashi et al. 2018). Moreover, many previous studies have proven that anthropogenic forcing influences the precipitation characteristics, such as precipitation amount (Boisier et al. 2016, Wang 2015, Heinzeller et al. 2016, Park et al. 2016, Tapiador et al. 2016, Konapala et al. 2017, Song et al. 2018) and precipitation extremes (Fischer and Knutti 2015, Mascioli et al. 2016, Angéll et al. 2017, Li et al. 2017, 2018, Ma et al. 2017, Sun and Miao 2018, de Abreu et al. 2019, Rimi et al. 2019), in many parts of GM regions. To what extent anthropogenic forcing influences rainfall seasonality remain largely unclear, however, particularly in GM regions.

Therefore, the objective of this study was to analyze the possible impacts of anthropogenic forcing on rainfall seasonality in GM regions using CMIP5 GCMs. This paper is organized as follows. Section 2 presents the datasets and a brief description of the methods. Sections 3 presents the results, followed by the main findings in section 4.

2. Data and methods

To assess the possible influences of anthropogenic forcing on rainfall seasonality in GM regions, we utilized the monthly precipitation outputs from 6 CMIP5 GCM simulations. These models were selected mainly based on the results of Pascale et al. (2015), and we just selected better performing models but excluded the worst performing models. All model outputs included external natural and human forcing (the ‘historical’ experiment, hereafter simply referred to as ALL) from 1850 to 2005, and 3 model outputs included external natural forcing (the ‘natural’ experiment, hereafter simply referred to as Nat) from 1850 to 2012. In addition, the future greenhouse gas emissions Representative Concentration Pathway 8.5 (RCP8.5) from 2006 to 2012 was used to replace missing historical simulations. In this study, we approximated the anthropogenic forcing (hereafter simply referred to as Ant) as the difference between the ALL and Nat seasonality indices derived from the CMIP5 models outputs (i.e. ALL – Nat). More details concerning the CMIP5 GCMs used in this study are provided in Table S1 (available online at stacks.iop.org/ERL/15/104057/mmedia).

The seasonality indices proposed by Feng et al. (2013) were used to describe rainfall seasonality in this study. The months in hydrological year k were indexed using m ∈ [1, 12]. For each year k, the annual rainfall is defined as $R_k = \sum_{m=1}^{12} r_k, m$ (and the associated distribution, $p_k, m = r_k, m/R_k$), where $r_k, m$ is the monthly rainfall amount in each hydrological year. RE is defined as $D_k = \sum_{m=1}^{12} p_k, m \log(2(p_k, m/q_m))$, where $q_m$ is the uniform distribution, such that each month has a value of 1/12. RE denotes the concentration of annual rainfall. Finally, the seasonality index (SI) could be expressed as $S_k = D_k / D_{\text{max}}$, where $D_{\text{max}}$ is the maximum R of all the CMIP5 model outputs used in this study or the maximum R of the observed precipitation dataset. Furthermore, the annual seasonality could be decomposed into annual rainfall, as well as the
timing and the duration of the wet season (Pascale et al. 2015). The annual rainfall indicates the magnitude of annual seasonality, while the timing and duration describe the arrival time and length of the wet season, respectively, in the monsoon-dominated regions. In information theory, these decomposed seasonality indices depend on the demodulated amplitude, the demodulated phase, and the entropic spread. For hydrological year \( k \), the annual rainfall is defined as \( R_k = \sum_{m=1}^{12} r_k m \), where \( m \) is the monthly index. The centroid \( C_k \) (timing) is expressed using the first of \( r_k, m \) as \( C_k = \frac{1}{R_k} \sum_{m=1}^{12} m r_k m \). The spread \( Z_k \) (duration) is interpreted as the number of effective months during the wet season, and is defined by \( Z_k = 12 \times 2^{-D_k} \). For more details concerning these seasonality indices, please refer to Feng et al. (2013) and Pascale et al. (2016).

Since the differences among the GM regions identified by the Global Precipitation Climatology Project (GPCP; Adler 2018) and the CMIP5 models appeared to be minor (Pascale et al. 2016), we used the 1979–2010 climatological precipitation from GPCP to identify the global land monsoon (GM) regions. Following Zhang et al. (2018), the GM regions were defined as the areas in which both the local ‘summer minus winter’ rainfall rate exceeded 2.0 mm day\(^{-1}\) and the local summer rainfall exceeded 55% of the annual total rainfall. Local summer is defined as the period from May to September in the Northern Hemisphere, and the period from November to March in the Southern Hemisphere.

The CMIP5 models were compared with the University of East Anglia’s Climatic Research Unit (CRU; Harris et al. 2020) and the GPCP (1979–2012) observed precipitation dataset over the global land monsoon regions. Because of the sparseness of observed data before 1960 (Schneider et al. 2014), so we choose the period 1960–2012 when validate CMIP5 models’ simulation by using the CRU precipitation dataset. The study period 1960–2012 was also selected in this study. To analyze the different influence patterns of anthropogenic forcing on rainfall seasonality in GM regions, we further applied the probability density functions (PDFs) estimated by the kernel smoothing method to compare the probability distributions of the ALL and Nat simulations’ seasonality indices over the monsoon regions. The probability distributions of seasonality indices in the CMIP5 models simulations are constructed with data from all the CMIP5 models used in this study. The confidence intervals at the 5th to 99th percentiles were estimated from 5000 bootstrapped subsamples. The subsamples were randomly resampled with replacement during bootstrapping.

CMIP5 models generally perform poorly when simulating the variations of climate variables, particularly precipitation, leading to biases in rainfall seasonality (Pascale et al. 2015). To increase the robustness of the results in this study, the measures proposed by Chen and Sun (2017) were applied to the data analysis. First, we analyzed all results using the multi-model ensembles based only on the CMIP5 simulations, without reference to observations. Second, we averaged the multi-model ensemble members of each model to ensure equal weight in the multi-model analysis. All calculations were conducted on native grids in each model, but the results were interpolated to 2.5 × 2.5 degrees grids by using the bicubic interpolation method when spatial patterns were present.

3. Results

3.1. Evaluation of CMIP5 model performance using the CRU and GPCP precipitation dataset

To evaluate the reliability of the CMIP5 model outputs for rainfall seasonality, we first compared the climatologies (figure 1) of the seasonality indices from the CRU precipitation dataset and the CMIP5 ALL historical simulations multi-model ensemble mean in GM regions from 1960 to 2012. Areas with the largest SI (figures 1(a) and (b)) were located in the northern parts of the South American, South African, North African, and Indian monsoon regions from both the CRU precipitation dataset and the CMIP5 simulation, with high spatial consistency. The results highly coincided with the findings by Pascale et al. (2016). In addition, climatologies of the concentration of annual rainfall, annual rainfall, and timing and duration of the wet season were all simulated well by the CMIP5 models compared with the CRU precipitation dataset (figures 1(c) and (j)), and consistent biases of the seasonality indices simulated by the CMIP5 models were apparent over transitional areas, such as the RE in Southeast China. The differences in climatologies between the CRU and the multi-model ensemble mean of the CMIP5 ALL historical simulations were considerable large, especially for SI and annual rainfall, but still in the 50th percentile range over the most parts of GM regions (figure S1). Moreover, climatologies of seasonality indices were also simulated well by the CMIP5 models compared with the GPCP precipitation dataset during the period 1979–2012 (figure S3). Therefore, the CMIP5 models captured the climatology of rainfall seasonality in global land monsoon regions to some extent.

Figure S2 presents the spatial patterns of the trend in seasonality indices from the CRU precipitation dataset and the multi-model ensemble mean of the CMIP5 ALL historical simulations in GM regions. The SI (figure S2(a)) and concentration of annual rainfall (figure S2(c)) increased in most parts of the GM regions, but tended to decrease in many parts of the East Asian monsoon region. Also, the SI trend from the CRU precipitation dataset agreed with that from the CMIP5 models in most parts of the GM regions, while exhibiting some inconsistency, especially in the North African monsoon region.
Annual rainfall and the timing of the wet season from the CRU rainfall dataset displayed good consistency with the corresponding parameters simulated by the CMIP5 models in almost all GM regions (figures S2(e), (g)). The duration of the wet season (figure S2(i)) tended to decrease in most parts of the GM regions, although it increased in some areas, particularly the northern parts of the East Asian monsoon region. The trends of seasonality indices simulated by the CMIP5 models’ ALL historical simulations were consistent with that from CRU precipitation dataset over the most parts of GM regions (figure S2(b), (d), (f), (h), and (j)). The CMIP5 models captured the trend of seasonality indices in the most parts of the GM regions. In addition, the trend of seasonality indices were also simulated well by the CMIP5 models compared with the GPCP precipitation dataset during the period 1979–2012 (figure S4). Note that the trend of seasonality indices from the GPCP precipitation dataset also significant at 90% confidential level over many parts of GM regions (figure S4(a), (c), (e), (g), and (i)). Overall, agreement of seasonality indices between the observed precipitation dataset (CRU and GPCP) and the CMIP5 ALL historical simulations in
the GM regions was reasonable, although some discrepancies were present.

3.2. Possible impacts of anthropogenic forcing on rainfall seasonality in GM regions

To understand the spatial differences of anthropogenic forcing impacts on rainfall seasonality, we analyzed the multi-year mean (figure 2) and trend (figure 3, estimated by Şen’s slope) of the Ant-related seasonality indices at each grid location in the GM regions, and also counted both of these over each monsoon region (shown in figures S5 and S6, respectively). Generally, anthropogenic forcing was found to enhance rainfall seasonality, exhibiting an increasing trend in almost all GM regions, particularly in the South Asian (average 0.015, trend 0.00007 yr⁻¹)
Figure 3. Spatial patterns of the multi-model ensemble median trend in (a) SI, (b) RE, (c) rainfall, (d) timing, and (e) duration attributed to anthropogenic forcing over the period 1960–2012. Areas where at least 2/3 of the models agree on the sign of the trend are marked with stippling; Bold gray lines denote the GM regions.

and the most parts of the South American and South African monsoon regions. In the South Asian monsoon region, anthropogenic forcing enhanced the concentration of annual rainfall (average 0.03) with an upward trend, and also increased annual rainfall amount (average 100 mm) with an increasing trend. By the way, rainfall seasonality was enhanced in this region. Anthropogenic forcing enhanced the concentration of annual rainfall with an increasing trend, and shortened the duration of the wet season with a decreasing trend in the most parts of the South American and South African monsoon regions. In the southern parts of the East Asian and Southeast Asian monsoon regions, anthropogenic forcing tended to increase the concentration of annual rainfall with an increasing trend, but reduce...
the amount of annual rainfall with a decreasing trend. In addition, the duration of the wet season was shortened, but with a decreasing trend under anthropogenic forcing in the Southeast Asian (average $-0.65$ months, trend $-0.0052$ months yr$^{-1}$) and the southern parts of East Asia monsoon regions. In the most parts of the North African monsoon region, delayed timing of the wet season and a long duration of the wet season with a decreasing trend tended to occur under anthropogenic forcing.

Anthropogenic forcing partially but clearly contributed to the increasing trend of rainfall seasonality in all GM regions. Figure S6 also presents the trends of the seasonality indices derived from the ALL and Nat simulations in each monsoon region. The trends of the ALL and Ant SIs were considerably pronounced and exhibited with the same increasing trend, but the Nat SI trend was not obvious in GM regions except in Australian monsoon region. Anthropogenic forcing contributed significantly to the enhanced rainfall seasonality in GM regions. This is because anthropogenic forcing tended to partly or largely influence the trends of RE, annual rainfall, and the timing or duration of the wet season, and enhanced rainfall seasonality in all GM regions (figures S6(b), (c), (d), and (e)). Particularly in the South American and North African monsoon regions, the trends of all corresponding ALL and Ant seasonality indices are significant and exhibited the same decreasing or increasing trends, although the Nat simulations displayed no trend. Anthropogenic forcing signal for the trend of rainfall seasonality was very apparent in these regions. Note that the continuously shortening duration of the wet season was largely associated with anthropogenic forcing in the Southeast Asian, East Asian, and South American monsoon regions (figure S6(e)).

Anthropogenic forcing increased the probability of more pronounced rainfall seasonality in almost all GM regions. The PDF distributions of the SIs simulated by the ALL realizations exhibited an obvious rightward shift relative to the Nat ensemble simulations in all monsoon regions, but not significant at the 5% confidence level in the Southeast Asian and North American monsoon regions (figure 4). Anthropogenic forcing increased the probability of mid-high values of the SI and correspondingly reduced the probability of mid-low values of the SI in the

**Figure 4.** Probability density functions (PDFs) estimated by the kernel smoothing method for the SI from all the CMIP5 models used in this study over monsoon sub-regions during the period 1960–2012. Red and green lines and shadings are historical multi-model with all forcing (ALL) and natural forcing only (Nat), respectively. Shaded areas denote 5th–95th confidence intervals derived from bootstrapping. Black asterisk indicates the difference between the two PDFs from ALL and Nat are statistically significant at the 5% confidence level by using the Kolmogorov-Smirnov test. Regional monsoon are depicted on the map in different colors.
East Asian, South Asian, South American, and South African monsoon regions. These influence patterns were especially evident in the South Asian and South American monsoon regions, since anthropogenic forcing increased (reduced) the probability of mid-high (mid-low) values of both the RE (figure S7) and annual rainfall (figure S8) in these regions.

Since the PDF distributions of the ALL RE also exhibited an obvious rightward shift relative to the Nat ensemble simulations in all GM regions (figure S7) but not significant in the North African Monsoon region, anthropogenic forcing increased the probability of higher concentrations of annual rainfall. Extremely high or low annual rainfall totals are likely to occur in the North African, South Asian, Australian, East Asian, and Southeast Asian monsoon regions under anthropogenic forcing (figure S8). The impacts of anthropogenic forcing on annual rainfall were not significant at the 5% confidence level in the South American and North American monsoon regions. The timing of the wet season was also affected by anthropogenic forcing, making the early onset of the wet season more likely in the Australian monsoon region, and the delayed onset of the wet season more likely in the North African, North American, East Asian, Southeast Asian, and South African monsoon regions (figure S9). In addition, anthropogenic forcing increased the probability of shortened wet season in all GM regions, but not significant at the 5% confidence level in the North African monsoon region. Note that extremely shortened or lengthened wet seasons were likely to occur in the Australian monsoon region under anthropogenic forcing (figure S10).

4. Discussion and conclusions

Anthropogenic activities have changed not only the trends but also the temporal variability of annual precipitation (Konapala et al 2017). Anthropogenic forcing has resulted in decreased uniformity in annual precipitation amount and intensity at global as well as continental scales (Konapala et al 2017). It has also been a key factor driving precipitation changes in tropical and monsoon regions (Polson et al 2014, Undorf et al 2018), southeastern South America and the southern Andes (Vera and Diaz 2015), and central Chile (Boisier et al 2016). These findings may explain why anthropogenic forcing influences annual rainfall in these regions, which is consistent with our results (figure 2(c)).

Changes in the global precipitation cycle, especially rainfall extremes, have been attributed to anthropogenic forcing (Tapiador et al 2016). The daily precipitation extremes over global land are attributable to anthropogenic forcing, especially during summer (Fischer and Knutti 2015). In addition, anthropogenic forcing has contributed to the observed intensification of heavy precipitation events discovered over approximately two-thirds of the data-covered regions of Northern Hemisphere land areas (Min et al 2011). These findings may explain why anthropogenic forcing enhances the concentration of annual rainfall (figure 2(b)) and shortens the duration of the wet season (figure 2(e)) in the most parts of land monsoon regions of Northern Hemisphere. Under anthropogenic warming, tropical rainfall tends to be shifted southward in April–June relative to July–September, manifesting in a seasonal delay of monsoon onset in the most parts of Northern Hemisphere (Song et al 2018). These results are in agreement with our results, as shown in figure 2(d). By affecting change patterns of RE, annual rainfall, and the timing or duration of the wet season, anthropogenic forcing may influence rainfall seasonality in GM regions (figure 2(a)).

Rainfall seasonality is closely associated with floods and droughts and influences many ecosystems. In this study, we quantitatively analyzed the impacts of anthropogenic forcing on rainfall seasonality in GM regions using 6 CMIP5 GCMs. We carefully drew the conclusion that anthropogenic forcing enhances rainfall seasonality over many parts of GM regions. Spatially, anthropogenic forcing enhances rainfall seasonality with an increasing trend from 1960 to 2012 over many parts of GM regions, particularly in the South Asian and the most parts of South American and the South American monsoon regions. The continuously shortening duration of the wet season is largely associated with anthropogenic forcing in the Southeast Asian, East Asian, and South American monsoon regions. Furthermore, anthropogenic forcing also increases the probability of more pronounced rainfall seasonality and higher concentrations of annual rainfall in almost all GM regions. Our results will be of immense assistance to policymakers in the devising of robust strategies for the adaption various sectors, such as agriculture, water resources, and energy, to changing rainfall seasonality under climate warming induced by anthropogenic forcing.

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Data availability statement

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

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