Spatial and Temporal Variations in Precipitation Amount, Frequency, Intensity, and Persistence in China, 1973–2016

HUA SHANG

Department of Ecology, Evolution and Natural Resources, Rutgers, The State University of New Jersey, New Brunswick, New Jersey

MING XU

College of Environment and Planning, Henan University, Kaifeng, China, and Department of Ecology, Evolution and Natural Resources, Rutgers, The State University of New Jersey, New Brunswick, New Jersey

FEN ZHAO

Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China, and Department of Ecology, Evolution and Natural Resources, Rutgers, The State University of New Jersey, New Brunswick, New Jersey

SADIYA BABA TIJJANI

Department of Ecology, Evolution and Natural Resources, Rutgers, The State University of New Jersey, New Brunswick, New Jersey

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ABSTRACT

In this paper, we examined the spatial and temporal variations in precipitation amount, frequency, and intensity in China based on daily precipitation data from 2050 weather stations from 1973 to 2016. We used two Markov chain parameters to quantify the wet persistence and dry persistence that characterizes the temporal pattern of wet and dry days, respectively. We found that China's annual precipitation changed little from 1973 to 2016, but varied dramatically from 524 to 688 mm yr⁻¹, with an average of 592 mm yr⁻¹, during this period. China's precipitation frequency, the number of days with effective precipitation (>0.1 mm day⁻¹) in a year, significantly decreased at a rate of 0.9 days decade⁻¹ from 1973 to 2016, but precipitation intensity significantly increased at a rate of 0.12 mm day⁻¹ decade⁻¹ during the same period. Of the changes in China's total precipitation amount, precipitation intensity played a dominant role, contributing 70.8%, while precipitation frequency contributed the remaining 29.2%. Little change was found in the wet persistence in China over the period of 1973–2016, but the dry persistence significantly increased with an average increasing trend of 1.62×10^{-3} probability per decade during the same period, and no significant correlations were found between these two variables. China's precipitation also changed nonuniformly in space, with increasing trends in precipitation amount, frequency, intensity, and wet persistence in western and northeastern China but decreasing trends in the Sichuan basin, northeast of Inner Mongolia, and the Beijing–Tianjin–Hebei region.

1. Introduction

Greenhouse gas–induced global warming has considerable impacts on precipitation (Dore 2005; Trenberth 2011; O’Gorman 2015) as the water-holding capacity

of air increases about 7% with every 1°C increase in air temperature (Trenberth 2011). Meanwhile, warming temperatures decrease atmospheric stability, resulting in stronger convections and thus more heavy precipitation events, as evidenced in various parts of the world (Fowler and Hennessy 1995; Allan and Soden 2008; Min et al. 2011; Zhang et al. 2013). The changes in global atmospheric circulation and hydrological cycle caused by warming temperatures may also lead to changes in spatial and temporal patterns of precipitation

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Corresponding author: Ming Xu, ming.xu@rutgers.edu

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(Ziegler et al. 2003; Huntington 2006; Allan and Soden 2008; O’Gorman and Schneider 2009; Zhang et al. 2013). Additionally, climate change–induced changes in evapotranspiration resulting from vegetation growth (e.g., through CO₂ fertilization and growing season elongation) and human activity (e.g., nitrogen fertilization and irrigation) may also affect precipitation in space and time (Bala et al. 2006; Leipprand and Gerten 2006; Kim and Wang 2007; DeAngelis et al. 2010; Pei et al. 2016).

Precipitation can be characterized by various indicators, such as annual total amount, frequency, duration, and intensity (Trenberth et al. 2003; Zolina et al. 2010; Guilbert et al. 2015; Hu et al. 2017; Trenberth and Zhang 2018). Any change in these precipitation characteristics may lead to an increase or decrease in water use efficiency and thus affect water resource planning and management practices. In addition, changes in extreme precipitation events may result in devastating effects on human society and their living environment. For example, a decrease in precipitation amount may cause drought, while an increase in precipitation intensity, frequency, and wet persistence may exacerbate soil erosion and trigger flooding and other disasters.

Climate change, especially precipitation change, has concerned China in many ways because China has often seen flooding in the southern regions while simultaneously experiencing droughts in the northern and northwestern regions of the country (Zhai et al. 2005). Previous studies found that the annual precipitation in China did not show any statistically significant trend in the past decades, but that precipitation frequency significantly decreased and thus precipitation intensity increased accordingly during the same period (Liu et al. 2005; Zhai et al. 2005; You et al. 2011; Zhang and Cong 2014; Ma et al. 2015; Wu et al. 2016). Other studies also found that China’s precipitation change is not homogeneous in space, with increasing precipitation in western and southeastern China and decreasing precipitation in northern and northeastern China (Gong et al. 2004; Liu et al. 2008; Wang et al. 2011b; Q. Zhang et al. 2012; Wang et al. 2013; Li et al. 2015; Guan et al. 2017). However, most of the previous studies used a relatively small number of weather stations (272–741 stations) in their analyses, which may have limited their ability to reveal the details of precipitation changes in space given the high spatial variation of precipitation in China (Liu et al. 2005; Zhai et al. 2005). In addition, few studies have examined the wet and dry persistence of precipitation in China using direct observations of weather stations (Hu et al. 2017).

In the current study, we used a recently available dataset of 2426 weather stations (especially with a doubled number of stations in western China compared to previous datasets, where weather stations are generally sparsely distributed) covering an extended period of time from 1973 to the end of 2016. We have focused on analyzing spatial and temporal changes in precipitation amount, frequency, and intensity in China using this new dataset. We also used a first-order two-state Markov chain model to investigate the wet and dry persistence of precipitation in China over the past 44 years (1973–2016), as the Markov chain method has been demonstrably effective in characterizing the wet and dry persistence of precipitation over a geographical area (Goossens and Berger 1984; Fdez-Arroyabe Hernández and Martín-Vide 2012; Guilbert et al. 2015). The objectives of this study are 1) to examine the spatial and temporal changes in precipitation amount across China from 1973 to 2016, 2) to investigate the spatial and temporal changes in precipitation frequency and intensity, 3) to evaluate the contribution of the changes in precipitation frequency and intensity to the changes in precipitation amount, and 4) to characterize the spatial and temporal changes in wet and dry persistence in China in the past decades.

2. Data

Daily precipitation data from 2426 weather stations across China for the period of 1953–2016 were obtained from the National Meteorological Information Centre (NMIC), China Meteorological Administration. This dataset is based on version 3.0 of the national basic meteorology historical dataset in China (Yang and Li 2014). The distribution of the stations is shown in Fig. 1.

Unlike temperature, missing data for precipitation are difficult to fill in since most precipitation events are abrupt in time and space (Chen et al. 2010). Data gap filling may also introduce biases to time series trend analysis, particularly for extreme events (Brown et al. 2010; Henn et al. 2013). Therefore, we have used strict criteria to select appropriate stations and time periods in the current study. Most missing data occurred in the 1950s and 1960s, especially in the Tibetan Plateau where most of the weather stations started operation in the late 1960s and early 1970s. In the current study, we have focused on analyzing the data from 1973 to 2016 to minimize the percentage of missing data and to ensure the temporal uniformity of all the stations in this study. We hence removed the stations on coastal islands and any stations with more than 0.01% missing precipitation values in the original dataset. However, we

FIG. 1. The spatial distribution of the weather stations in China. Dots indicate the 2050 stations that were used in this study, while crosses represent the stations that were removed from our analysis. The background color shows the average annual precipitation amount in China during 1973–2016.

have applied a slightly relaxed criterion to weather stations in western China due to the relative scarcity of stations in this region. For such stations, the whole year was deleted from the analysis if the missing data were more than 1% in the year, and the whole station was excluded if the number of deleted years was more than three, in order to maintain a minimum sample size of 41 for trend (linear regression) analyses. To examine the impacts of missing 3 years on the trend analysis, we purposely and randomly deleted 3 years from the time series dataset for each station, then repeated the process 100 times to perform a Monte Carlo simulation for each station. We found that the slopes of the 100 simulations were not significantly different from each other ($p > 0.15$) and that each slope of the deleted dataset was also not statistically different from the slope computed based on the undeleted dataset ($p > 0.25$). As a result, 2050 stations were selected from the 2426 stations, with over 99.93% records complete during the study period, 1973–2016.

3. Methods

In this study, we considered wet days as daily precipitation $\geq 0.1 \text{ mm day}^{-1}$, which excludes very light precipitation (Liu et al. 2005). Precipitation frequency is calculated as the number of wet days, and precipitation intensity is calculated simply by dividing the total precipitation amount by the frequency. Changes in precipitation amount can be attributed to the change in precipitation frequency or in intensity (Karl and

Knight 1998). In the current study, we also estimated the contribution of changes in precipitation frequency and intensity to the change in precipitation amount, following the method introduced by Karl and Knight (1998). We first calculated the changes in precipitation amount caused by the change in precipitation frequency and intensity respectively. The frequency (intensity) component is estimated by multiplying the trend in precipitation frequency (intensity) by the average intensity (frequency):

$$C_{\text{freq}} = S_{\text{freq}} \times \overline{\text{int}}, \quad (1)$$

$$C_{\text{int}} = S_{\text{int}} \times \overline{\text{freq}}, \quad (2)$$

where C_{freq} (mm yr^{-1}) and C_{int} (mm yr^{-1}) are the changes in precipitation amount due to changes in precipitation frequency and intensity, respectively. The terms S_{freq} (days yr^{-1}) and S_{int} ($\text{mm day}^{-1} \text{ yr}^{-1}$) are the trends of precipitation frequency and intensity, and $\overline{\text{freq}}$ (days) and $\overline{\text{int}}$ (mm day^{-1}) are the averages of precipitation frequency and intensity, respectively.

Then, we further calculated the relative contributions of precipitation frequency and intensity using the following equations for comparative purposes:

$$R_{\text{freq}} = \frac{|C_{\text{freq}}|}{|C_{\text{freq}}| + |C_{\text{int}}|}, \quad (3)$$

$$R_{\text{int}} = \frac{|C_{\text{int}}|}{|C_{\text{freq}}| + |C_{\text{int}}|}, \quad (4)$$

where R_{freq} (%) and R_{int} (%) are the relative contributions of precipitation frequency and intensity to the change in annual precipitation amount, and $|C_{\text{freq}}|$ and $|C_{\text{int}}|$ denote the absolute values of C_{freq} and C_{int} .

Wet persistence, a good indicator for characterizing the distribution of precipitation in time, is the tendency for a rainy day following another rainy day, assuming that the probability of precipitation on any day depends only on whether the previous day was wet or dry (Mirza et al. 1998; Gabriel and Neumann 1962; Guilbert et al. 2015). Similarly, dry persistence is a good indicator for characterizing the temporal pattern of dry spells. In this study, the parameters of the first-order two-state Markov chain model were applied to assess the wet persistence (P11) and dry persistence (P00) according to Guilbert et al. (2015). The first-order Markov chain model assumes that the probability of precipitation on day t only depends on the state of the previous day $t - 1$. Let X_t indicate the state of precipitation on day t with 1 and 0 representing a wet and dry day, respectively. Then, P11 [Eq. (5)] is the probability of transition from a wet day to another wet day and P00 [Eq. (6)] describes the probability of transition from a dry day to another dry day:

$$P11 = \Pr\{X_t = 1 | X_{t-1} = 1\}, \quad (5)$$

$$P00 = \Pr\{X_t = 0 | X_{t-1} = 0\}. \quad (6)$$

The trends of the annual amount, frequency, intensity, and wet and dry persistence of precipitation for each station were determined by linear regression analyses and corresponding F tests were used to test the statistical significance of the trends at a 5% significance level for each station. We also compared the results of the F tests with those of the Mann–Kendall tests (a nonparametric approach), and found that the two methods gave very similar results (p values) (data not shown). The p values reported in the current study are based on the F tests. All statistical analyses were conducted using SAS software (version 9.4).

It is noted that the 2050 meteorological stations are not evenly distributed across the country, with fewer stations in western China and more stations in central and eastern China. To estimate the spatial average for the whole country, Thiessen polygons were created using ArcGIS software (version 10.2.2) to determinate the “footprint” area that each station “controls,” and then each variable was spatially averaged according to the footprint-based weighting factor for each station and each year. The trends of each variable for the whole country were also determined by linear regression analyses during the study period. Also, instead of

the conventional method of dividing a year into four equal seasons, a monsoon-based season division method was deemed more appropriate for analyzing the characteristics of seasonal precipitation in China, as used in previous studies (Liu et al. 2005). Hence, we classified monsoon seasons by dividing the year into winter monsoon season (October–March), spring transition season (April and May), summer monsoon season (June–August), and fall transition season (September). Many previous studies have shown that climate change, such as the linear trends of temperature and precipitation, has a much larger footprint than the climate variables themselves (Hegerl et al. 2006). Therefore, in this study we did spatial interpolations on the trends using the kriging interpolation method in ArcGIS software (version 10.2.2) for better visualizing the spatial patterns of the linear trends of various precipitation characteristics.

4. Results and discussion

a. Changes in precipitation amount

The annual total precipitation amount, weighted by the footprint-based weighting factor of each station, in China varied dramatically from 524 to 688 mm yr^{−1}, with an average of 592 mm yr^{−1}, during the study period from 1973 to 2016. The precipitation did not show a significant trend ($p = 0.27$) during this period, although the trend did slightly increase by a mere 4.5 mm decade^{−1} (Fig. 2a). Our result confirms the findings of previous studies that the annual precipitation of the whole country of China did not show any significant increasing or decreasing trends in the past decades (Liu et al. 2005; Zhai et al. 2005; You et al. 2011; Zhang and Cong 2014; Feng and Zhao 2015; Ma et al. 2015; Wu et al. 2016). We further examined China’s precipitation by season and failed to find any significant trend for any season (spring, summer, fall, or winter) from 1973 to 2016 (Fig. S1a in the online supplemental material). The average rate of increase in precipitation (0.76% decade^{−1}) in the current study is considerably higher than that reported in earlier studies. For example, Zhai et al. (2005) reported an increasing precipitation trend of 0.24% decade^{−1} from 1951 to 2000 and Wu et al. (2016) found an increasing trend of 0.09% decade^{−1} from 1960 to 2012. The significant increase in China’s precipitation in the most recent decade might be the reason for the greater increasing trend from 1973 to 2016 (Fig. 2a). In addition, the change in precipitation amount in China differs from the trends in many other regions in the Northern Hemisphere. The average rate of increase of 0.76% in China’s precipitation as found in the current study is comparable

FIG. 2. (a) Time series of annual precipitation amount over the entirety of China from 1973 to 2016. (b) Time series of precipitation frequency (solid circles) and intensity (triangles) over the entirety of China (spatially weighted) from 1973 to 2016. The dotted line and dashed line indicate the significant annual trends for precipitation frequency and intensity, respectively.

to that of west Eurasia's rate of 0.65% decade $^{-1}$ from 1961 to 2012 (Zhao et al. 2018). However, this increasing rate of precipitation in China is much lower compared to the United States' 1.66% decade $^{-1}$ from 1951 to 2013 (Wu 2015) or to Canada's 2.92% decade $^{-1}$ from 1948 to 2012 (Vincent et al. 2015).

We also found that the change in China's precipitation from 1973 to 2016 was not uniform in space (Fig. 3). The precipitation significantly increased in northeastern, southeastern, and western China, including the Tibetan Plateau. Meanwhile, the annual precipitation decreased along a geographical band from southwestern China to the northeast of Inner Mongolia, with significant decreases found in the Yunnan–Guizhou Plateau, Sichuan basin, and the Beijing–Tianjin–Tangshan region (Fig. 3). Our findings that the precipitation amount significantly increased in northeastern China but decreased in southwestern China (mainly Yunnan

province) are different from the results of earlier studies (Zhai et al. 2005; Zhang and Cong 2014). The discrepancies are mainly caused by the dramatic increase in precipitation in the northeast and a corresponding decrease in the southwest since the beginning of the twenty-first century (Fig. S2) (Li et al. 2015), a time period that previous studies did not include in their analyses. Our results of the spatial patterns in precipitation amount that increased in southeastern China and decreased in the geographical band from southwestern China to the northeast of Inner Mongolia confirm the weakening of the summer monsoon in China (Gong and Wang 2000; Ding et al. 2008; Wu et al. 2016). Interestingly, we found that the regions with significantly decreasing precipitation were also the areas with the most severe air pollution, especially in high SO_2 emissions from coal burning (X. Zhang et al. 2012; Fioletov et al. 2016; Wang et al. 2018). Previous studies have reported

FIG. 3. Spatial distribution of annual trends in total precipitation amount (mm yr^{-1}) in China, 1973–2016. Circles represent a significant increase, crosses indicate a significant decrease, and small dots indicate nonsignificant changes.

that aerosols from air pollution can suppress precipitation (Rosenfeld 2000; Ramanathan et al. 2001). For example, Givati and Rosenfeld (2004) found that urban and industrial pollution could decrease regional precipitation by up to 25% in major urban areas in coastal California and the land of Israel. However, the mechanism of whether the decreasing precipitation exacerbated the air pollution or the air pollution led to the decrease in regional precipitation is complex, and further studies are needed.

b. Changes in precipitation frequency and intensity

The spatially weighted (with the Thiessen polygon method) annual precipitation frequency [the total number of days with effective precipitation ($>0.1 \text{ mm day}^{-1}$) in a year] in China varied from 89 to 102 days yr^{-1} with an average of 96 days yr^{-1} during the study period from 1973 to 2016. Although the annual total precipitation amount did not change significantly in China in the past decades, precipitation frequency has significantly decreased ($p = 0.02$) from 1973 to 2016, with an average rate of decline of 0.9 days decade^{-1} (Fig. 2b). However, this declining trend in China's precipitation frequency was not uniform throughout the whole study period. We found that the precipitation frequency significantly ($p = 0.03$) decreased from 1973 to 2006, but variably increased since then, although the increasing trend was not statistically significant ($p = 0.27$) (Fig. 2b). We further examined China's precipitation frequency by season and found that from 1973 to 2016, the precipitation frequency decreased for all four seasons, but that only the summer trend was statistically significant

($p = 0.02$) (Fig. S1b). This indicates that the decreasing trend in annual precipitation frequency was mostly contributed by summer precipitation events.

The decline in precipitation frequency yet lack of change in total precipitation amount has, as expected, resulted in a significant increase in China's precipitation intensity ($p < 0.01$). We found that China's precipitation intensity increased by $0.12 \text{ mm day}^{-1} \text{ decade}^{-1}$ from 1973 to 2016 (Fig. 2b). Furthermore, we found that the precipitation intensity significantly increased across all seasons ($p < 0.04$), with an average rate of increase of 0.10, 0.15, 0.16, and $0.11 \text{ mm day}^{-1} \text{ decade}^{-1}$ in winter, spring, summer, and fall, respectively (Fig. S1c).

Like the change in precipitation amount, the changes in precipitation frequency and intensity in China over the past decades were not homogenous in space (Figs. 4a,b). Precipitation frequency decreased in most parts of China from 1973 to 2016 with significant decreases in southwestern and southeastern China, but increased in western and northeastern China, especially in the southwestern Xinjiang Autonomous Region, where most of the weather stations experienced a significant increase in precipitation frequency ($p < 0.05$) (Fig. 4a). Meanwhile, China's precipitation intensity has increased in most parts of the country except Sichuan basin, northeast of Inner Mongolia, and the Beijing–Tianjin–Hebei region, where the precipitation intensity has experienced a declining trend (Fig. 4b). Despite this, very few weather stations in those regions have seen a large enough decreasing trend in precipitation intensity to be deemed significant (Fig. 4b). Most significant increasing trends ($p < 0.05$) in precipitation

FIG. 4. Spatial distribution of annual trends in (a) precipitation frequency (days yr^{-1}) and (b) intensity ($\text{mm day}^{-1} \text{yr}^{-1}$) in China, 1973–2016. Circles represent a significantly increasing trend, crosses indicate a significantly decreasing trend, and small dots indicate nonsignificant changes.

intensity were found in southeastern, southwestern, and western China.

Our findings on the changes in China's precipitation frequency and intensity are, in general, consistent with the findings in previous studies (Liu et al. 2005; You et al. 2011; Zhang and Cong 2014; Ma et al. 2015; Wu et al. 2016). However, the average rate of the decreasing trend in the precipitation frequency ($-0.94\% \text{decade}^{-1}$) is lower than the rates found in earlier papers (Liu et al. 2005; Ma et al. 2015; Wu et al. 2016). For example, Liu et al. (2005) found a $-2.4\% \text{decade}^{-1}$ decrease from 1960 to 2000 and Wu et al. (2016) reported a $-1.96\% \text{decade}^{-1}$ decrease from 1960 to 2013. This is likely due to the exclusion of the 1960s in the current study, as Zhang and Cong (2014) found that the 1960s had a high precipitation

frequency in China. This significant decrease in China's precipitation frequency was also in agreement with the findings reported for Italy (Brunetti et al. 2000, 2004), northern Eurasia (Ye et al. 2016), and Southeast Asia (Endo et al. 2009), though an opposite trend was reported for the United States (Karl and Knight 1998), Australia (Suppiah and Hennessy 1998), and central Argentina (de la Casa et al. 2018), indicating the complexity of precipitation change under global warming (IPCC 2013).

c. Contribution of precipitation frequency and intensity to the change of precipitation amount

The change in annual precipitation amount is attributed to both changes in precipitation frequency and intensity (Karl and Knight 1998). For the entire country of

China, we found that the slightly increased annual precipitation was more associated with the significantly increased precipitation intensity during the study period of 1973–2016. The increased precipitation intensity contributed 70.8% to the change in precipitation amount, while the decreased precipitation frequency contributed the remaining 29.2%. The dominant and positive contribution of precipitation intensity was partially offset by the negative contribution (declining trend) of precipitation frequency, leading to a slightly increasing trend in the precipitation amount in China (Figs. 2a,b).

However, our result that the increasing precipitation intensity contributed more to the change in China's precipitation amount differs from the finding in Wu et al. (2016) that the little increasing precipitation amount was more associated with the decreasing frequency instead of the increasing intensity. We also used the relative weights analysis according to Wu et al. (2016) to analyze the contributions of changes in precipitation frequency and intensity to the change in precipitation amount. The result that the increasing precipitation intensity accounts 69.7% to the total variance of precipitation change and the precipitation frequency only explained 6.38% is also consistent with our previous conclusion. The major disparity of the results between Wu et al. (2016) and our study might be caused by the differences in the time period for each station analyzed and the differences in stations used. Our finding that precipitation intensity contributed the most to the change of precipitation amount in the past decades in China is different from the results reported for other regions in the world, again indicating the heterogeneity of global precipitation change. For example, Karl and Knight (1998) found that the increase in precipitation frequency, not decrease, in the United States contributed 87% to the total precipitation change from 1910 to 1996.

Opposite directions of changes in precipitation frequency and intensity could be canceled each other out in many regions, resulting a weak trend in annual precipitation amount. However, a significant change in either the precipitation frequency or the intensity could have large impacts on regional vegetation, soil, and streamflow even though with an unchanged precipitation on an annual scale. We further extended our analysis by classifying all 2050 weather stations into two groups: increase (1093 stations) versus decrease (957 stations) in precipitation amount. We found that for the precipitation increasing group, precipitation intensity was dominant, contributing 97.1% of the changes in precipitation amount. But for the group with decreasing precipitation, precipitation frequency stood out, accounting for 86.4% of the total precipitation change with precipitation intensity contributing merely 13.6%.

Although most stations show little change in total precipitation in China (Fig. 3), different stations and regions might experience different disasters due to the changes in either precipitation frequency or intensity. The precipitation increasing group, major in the southeastern, northeastern, and western China, has a higher risk of experiencing soil erosion and flooding due to the increased precipitation intensity, while the decreasing precipitation group in the southwest and middle of China has a higher probability of experiencing drought caused by the decreased wet days.

d. Changes in wet and dry persistence

The wet persistence, the probability of a wet day given that the previous day was wet, for China as a whole did not show any significant trend ($p = 0.62$) from 1973 to 2016 (Fig. 5a). This means that the temporal distribution of China's annual wet days did not change markedly in the past decades, although the total number of wet days has significantly decreased (Figs. 2b and 5a). However, we found that the dry persistence, the probability of a dry day given that the previous day was dry, significantly increased in China from 1973 to 2016 ($p = 0.04$), with an average increasing trend of $1.62 \times 10^{-3} \text{ decade}^{-1}$ (Fig. 5a). In the current study we found that not only had the total number of dry days in China increased (as indicated by the decreasing precipitation frequency), but that the temporal distribution of these dry days had also changed, as evidenced by the greater probability of consecutive dry days. Our results are opposite to the findings reported for the northeastern United States, where the wet persistence significantly increased while the dry persistence barely changed in the past decades (Guilbert et al. 2015). Although both China and the United States are experiencing increasing precipitation, the distribution of global precipitation in time is heterogeneous. Our findings may explain the more frequent droughts in China and the upsurge in flooding in the northeastern United States in the past decades (Smith et al. 2011; Wang et al. 2011a; Peterson et al. 2013; Yu et al. 2014). Spatially, significant decreasing in wet persistence was mostly found in south China (Fig. 6a), especially in Yunnan–Guizhou Plateau and western Sichuan basin, together with the significantly increased dry persistence in those region (Fig. 6b), indicating a higher risk of drought in southern China.

As one may expect, the dry and wet persistence could complementally relate to each other and, indeed, Hu et al. (2017) reported a significantly negative correlation between the wet and dry persistence in China using a spatially interpolated dataset. In this study, however, we found that the wet and dry persistence were very weakly correlated (Fig. 5b). And we

FIG. 5. (a) Time series of wet (solid circles) and dry (triangles) persistence over the entirety of China (spatially weighted) from 1973 to 2016. The dashed line indicates the significant annual trend for dry persistence. (b) Correlation between wet and dry persistence.

further analyzed the relationships between wet and dry persistence for each station, and found that 89.7% of the stations in China show very weak correlations ($p > 0.05$) between these two variables. This discrepancy may be attributed to the difference between the direct station observations (e.g., current study) and the spatially interpolated data as used in the analysis of Hu et al. (2017). Spatial interpolation of daily precipitation to $0.5^\circ \times 0.5^\circ$ grids might introduce large biases to the wet and dry persistence analyses (the Markov chain model) due to the high spatial variability of the Asian monsoon storms (Hoyos and Webster 2007; Paul et al. 2018).

5. Conclusions

In this study, the spatial and temporal variations in precipitation amount, frequency, and intensity in China were examined based on daily precipitation data from 2050 weather stations during 1973–2016. And we also

used two Markov chain parameters to quantify the distribution patterns of wet and dry days in time. Our result showed that the annual precipitation amount for China as a whole did not change significantly from 1973 to 2016, but varied dramatically from 524 to 688 mm yr^{-1} , with an average of 592 mm yr^{-1} , during this period. Spatially, precipitation significantly increased in northeastern, southeastern, and western China, especially the Tibetan Plateau, but decreased in the northeast of Inner Mongolia, Yunnan–Guizhou Plateau, Sichuan basin, and the Beijing–Tianjin–Tangshan region. Interestingly, the regions with significantly decreasing precipitation were consistent with the most severely air-polluted areas. However, further studies are needed on whether the decreasing precipitation exacerbated the air pollution or the air pollution led to the decrease in regional precipitation.

An unchanged precipitation amount might be occurred even when the changes in precipitation frequency and intensity are both significant, which could

FIG. 6. Spatial distribution of annual trends in (a) wet persistence (probability yr^{-1}) and (b) dry persistence (probability yr^{-1}) in China, 1973–2016. Circles represent a significantly increasing trend, crosses indicate a significantly decreasing trend, and small dots indicate nonsignificant changes.

affect regional vegetation, soil, and streamflow as well. In China, although the annual total precipitation amount did not change significantly in the past decades, precipitation frequency has significantly decreased with a significantly increasing precipitation intensity from 1973 to 2016. Moreover, the increased precipitation contributed 70.8% to the slightly increased precipitation for China as a whole, while changes in frequency explained the remaining 29.2%. However, our result that the increasing precipitation intensity contributed more to the change in China's precipitation amount differs from the finding in Wu et al. (2016) that the little increasing precipitation amount was more associated with the decreasing frequency instead of the increasing intensity by using relative weights analysis. The data

used in this study kept a consistent starting and ending time for all stations compared to a relaxed time length used in Wu et al. (2016), and the number of stations used is more than triple the number of stations used in previous studies, which could be the reasons for this disparity. In addition, although the relative weights analysis is one of the most popular method that appears to overcome many of the problems when estimating the contribution each variable makes to the dependent variable, it is limited by the sample size (Lundby and Johnson 2006), for example when the study area only covers few stations or when trying to explore the contributions for each station. Except the analysis of contributions for the whole China, we further investigated the contributions of changes in precipitation

frequency and intensity to the changing precipitation amount for the 2050 weather stations in China. Our results showed that for the regions with increasing precipitation, the change in precipitation amount was mainly due to the enhanced precipitation intensity, while it was mainly attributed to a decline in precipitation frequency for the regions with decreasing precipitation in China. Areas with increased intensity as dominant contribution to the changing precipitation have a higher risk of experiencing soil erosion and flooding, while the regions with decreased precipitation frequency have a higher probability of experiencing drought.

Not only can the changes in total precipitation amount affect water resource management and the risk of flooding and drought, the changing distributions of precipitation in time also matters. Although little change was found in the wet persistence in China, the dry persistence significantly increased from 1973 to 2016, indicating an increased risk of drought due to the higher probability of consecutive dry days. Especially, significant decreased wet persistence, together with the significantly increased dry persistence in Yunnan–Guizhou Plateau and western Sichuan basin, suggesting a higher risk of drought in southwestern China. We did not find any significant correlations between the wet and dry persistence in China, though Hu et al. (2017) reported a significantly negative correlation between them using a spatially interpolated dataset. This discrepancy may be attributed to the difference between the direct station observations and the spatially interpolated data. All these changes in precipitation characteristics are important in understanding the spatial and temporal dynamics of China's water resources and hydrological cycles in the past decades.

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