  Hydrology Research | 49.4 | 2018

Changes in temporal inequality and persistence of precipitation over China during the period 1961–2013

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ABSTRACT

The spatial-temporal variability of precipitation is closely related to the occurrence of drought/flood, which thus merits close study. Here we examine the temporal inequality and persistence of precipitation over China from 1961 to 2013, through the use of Gini coefficient, Lorenz asymmetry coefficient and parameters (*P*00 and *P*11) of first-order Markov chain. The Mann-Kendall test was also applied to assess the changes in all indices used. The results showed that the temporal inequality of daily precipitation increased, associated with decreased wet days and increased heavy precipitation events, during the past century in most parts of China. The dry spell overall increased while wet spell declined during the period 1961–2013, which implied that the risks of both drought and flood would enhance over China in the future. However, the changes in temporal inequality and persistence of precipitation varied among sub-regions and basins, for example, extreme precipitation decreased in Songhua River basin and Pearl River basin but increased in other basins. The results obtained in this study would be helpful for understanding the spatial-temporal changes of precipitation (and thus drought and flood disasters) and for developing reasonable strategies for water resources management over China under the changing climate.

Key words | China, climate change, dry spell, Gini coefficient, precipitation, wet spell

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INTRODUCTION

Global climate change has accelerated terrestrial water cycle and changed the frequency and intensity of regional precipitation. Global averaged precipitation would increase by 1–3% while extreme precipitation would enhance by 7% when global temperature increases 1°C (Edenhofer & Seyboth 2013). The spatial-temporal variation of precipitation (e.g., concentrate or sparse during several months), which is closely related to drought and flood events, has important influences on agricultural production, flood control, drought resistance and human survival. Since the 1980s, the agricultural production and national economy (totally economic losses are 200 billion CNY which accounts for 3–6% of the total gross national product in China) have suffered very considerable losses over China due to droughts and floods (Yin & Li 2001; Wang 2007). It is thus critical to study the temporal variation of precipitation to further understand, project and adapt (e.g. reasonable strategy for water resource management) the potential risks of drought and flood under the changing climate.

One important feature of precipitation change is its temporal variability (i.e., frequency and types of precipitation). Some previous studies have shown that there are different change patterns in temporal distribution of precipitation, for example, the 'it never rains, but it pours' pattern, which indicates that more extreme rainfall events coexist with more continuous dry days (Trenberth 2010). Another change pattern shows that the extreme precipitation events

doi: 10.2166/nh.2017.083

would increase accompanied by the decrease in medium-sized precipitation events and continuous drought days (Rajah *et al.* 2014). During the past several years, many scholars have carried out relevant studies in China at different spatial and temporal scales (Zhai *et al.* 1999). For instance, Zhang *et al.* (2011) indicated that precipitation in northern China has declined (especially for Shandong province and the middle reach of Yellow River) during the period 1956–2000 based on monthly precipitation data from 590 meteorological stations over China. Zhai *et al.* (2014) studied the spatial-temporal variability of precipitation in Beijing during 1724–2010 using multiple methods (e.g., linear regression, moving average and Mann-Kendall test) based on 20 meteorological stations and indicated that annual precipitation rate has decreased. Ren *et al.* (2015) and Wang *et al.* (2015) analysed changes of precipitation over China using data from more than 1,800 stations.

To depict changes in precipitation frequency and types, several indicators are always used. For example, Shi *et al.* (2013) and Huang *et al.* (2015) studied the precipitation changes (trend and spatial pattern) in Lancang River Basin and Qinghai province using precipitation concentration index and Lorenz asymmetry coefficient. Liu *et al.* (2015) used a series of evaluation indicators (e.g., precipitation concentration) for describing precipitation inequality and for evaluating inhomogeneity of precipitation in China from 1960 to 2013. However, most studies focused only on some aspects (e.g., intensity, frequency or extreme) of precipitation change through the use of limited data (several hundred stations). The temporal inequality and persistence of daily precipitation, which is closely relevant to drought and flood risks, has not been comprehensively investigated especially using the gridded precipitation dataset with high resolution interpolated from more than 2,000 meteorological stations over China.

The objectives of this paper are: (1) to analyse the temporal inequality and persistence of daily precipitation over China, by comprehensively using multiple statistics (e.g., Gini coefficient, Lorenz asymmetry coefficient, the probabilities of rain and no rain, number of wet days (WD), median of precipitation amount and the 95th percentile of daily precipitation); and (2) to investigate their differences in 10 major basins of China for discussing the potential risks of regional droughts and floods. Data and methods adopted in this study are described below, followed by the obtained results and related discussion, and finally several conclusions are drawn.

DATA AND METHODS

Precipitation data

To examine the changes in spatial-temporal variability of precipitation over China, two precipitation datasets from 1961 to 2013 were used in this study. First, daily gridded precipitation (spatial resolution: $0.5^\circ \times 0.5^\circ$) from Meteorological Science Data Sharing Service Network of China Meteorological Administration (MSDSSN-CMA, http://cdc.cma.gov.cn/home.do), which was interpolated from 2,472 weather stations using the *ANUSPLIN* software. Secondly, daily precipitation from 523 weather stations, which was obtained from National Climate Centre of CMA (http//www.nmic.gov.cn/), was also applied to evaluate the accuracy of precipitation statistics calculated from the gridded dataset. The following statistics of daily precipitation were calculated at both site and grid scales. They were also averaged in 10 major river basins (Figure 1) which were defined by Ministry of Water Resources of China to consider varied regional climates and geographical features.

Methods

In this study, some commonly used statistics of daily precipitation, i.e., number of WD (daily precipitation $\geq$0.1 mm), median of precipitation amount (Median) and the 95th percentile of daily precipitation (Q95) (Guilbert *et al.* 2015) were applied to quantify general characteristics of precipitation over China. Moreover, the following indicators were also adopted to quantitatively evaluate the temporal inequality and persistence of precipitation.

Gini coefficient and Lorenz asymmetry coefficient

The Gini coefficient has been widely used in socioeconomic studies to measure the inhomogeneity of income distribution among families, societies and residents of a state. It has

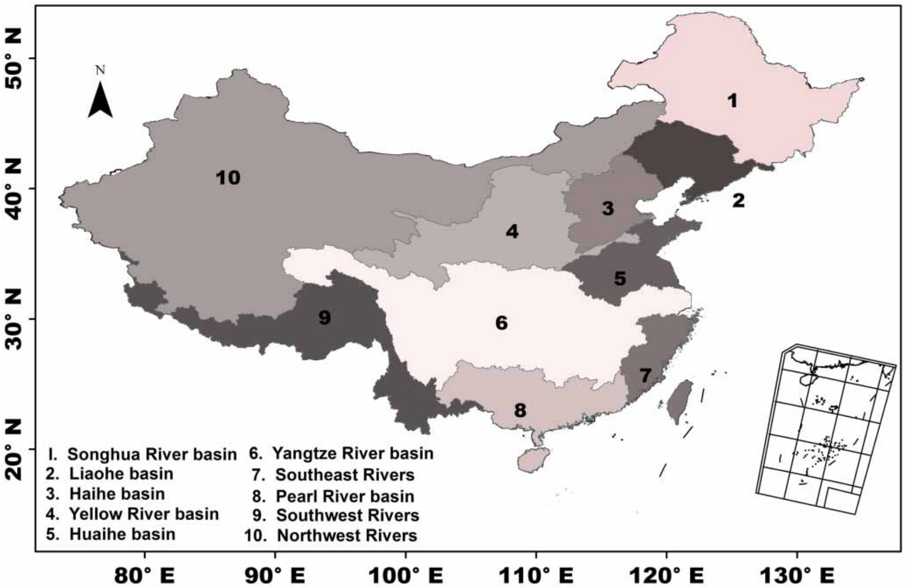

Figure 1 | Locations of 10 major basins over China.

recently been applied in hydrological studies to analyse the annual and inter-annual distribution of precipitation and streamflow (Jawitz & Mitchell 2011). In this study, the daily precipitation at one grid (station) was first arranged in ascending order. It was then summed cumulatively and converted to percentages of the total precipitation. A Lorenz curve was plotted with the accumulated time as the x-axis and the cumulative percentage of precipitation as the y-axis. The Gini coefficient can be calculated by doubling the area between the Lorenz curve and the 45° line (Rajah *et al.* 2014). It can be mathematically described as

$$G = \frac{1}{n}\left(n + 1 - 2\left(\frac{\sum_{i=1}^{n}(n+1-i)y_i}{\sum_{i=1}^{n} y_i}\right)\right) \quad (1)$$

where $i = 1 \cdots n$ (non-leap year $n = 365$, leap year $n = 366$); y_i is the amount of precipitation on a given day (if there is no precipitation on that day, y_i is 0). G ranges from 0 to 1. $G = 0$ indicates a uniform distribution of precipitation across all days (even) within the year while $G = 1$ means that all the precipitation occurs on a single day (uneven).

The Gini coefficient does not contain all information of the Lorenz curve; different Lorenz curves can have the same Gini coefficient (Masaki *et al.* 2014). To resolve this possible diversity, Lorenz asymmetry coefficient (*LAC*), which aims to quantify the reason for the temporal inequality of precipitation, was introduced as a supplementary index (Masaki *et al.* 2014). The combination of Lorenz curve and Gini coefficient is a more efficient way to describe the temporal inequality of precipitation (Shi *et al.* 2013). *LAC* can be calculated as (Damgaard & Weiner 2000):

$$S = F(\mu) + L(\mu) \quad (2)$$

$$\sigma = \frac{\mu - x_m}{x_{m+1} - x_m} \quad (3)$$

$$F(\mu) = \frac{m + \sigma}{n} \quad (4)$$

$$L(\mu) = \frac{L_m + \sigma x_m}{L_n} = \frac{\sum_1^m x_i + \sigma x_m}{\sum_1^n x_i} \quad (5)$$

x_i is the ordered number, μ is the mean of x, n is the total number of data points and m is the number of data points less than the mean. If $LAC > 1$, the temporal inequality of precipitation is mostly due to a small number of very large precipitation events while if $LAC < 1$, the inequality is due to a large number of very small precipitation events (Masaki *et al.* 2014).

Dry spell and wet spell

To quantify the persistence of wet and dry status, two parameters (*P00* and *P11*) in first-order Markov chain were also used in this study. The nature of first-order two-state Markov chain is no posterior effect, say the state value x at time t is assumed only related to the state value y at the previous time and is independent from the state value at other times (Lohani & Loganathan 1997). The parameter P_{ij} can be calculated as follows:

$$P_{ij}(n,k) = P(X_{n+k} = j|X_n = i) \tag{6}$$

$$P_{ij} = \frac{n_{ij}}{\sum_{i=1}^{s} n_{ij}} \tag{7}$$

The parameter $P00$ in this study represents the probability of a transition from a dry day to a dry day (Guilbert *et al.* 2015), in other words, the probability of maintaining the drought state. Conversely, $P11$ shows the probability of a transition from a wet day to a wet day.

Mann-Kendall trend test method

The Mann-Kendall test (Mann 1945; Kendall 1990), which is often used to quantify non-parametric trends in hydroclimatic time series (Subash *et al.* 2011; Duhan & Pandey 2013; Ping *et al.* 2014), was applied in this study to identify the trend in the above indices adopted. In the Mann-Kendall test, samples do not need to follow a given distribution and the result will not be disturbed by a few abnormal values. The S' in the Mann-Kendall test can be calculated as follows (Mann 1945):

$$S' = \sum_{\mathrm{i}=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \tag{8}$$

$$sgn(x_j - x_i) = \begin{cases} 1 & x_j - x_i > 0 \\ 0 & x_j - x_i = 0 \\ -1 & x_j - x_i < 0 \end{cases} \tag{9}$$

Here n is the number of data points; x_i and x_j are data values in the given time. S' follows the normal distribution with a mean of 0. The variance of S' is as follows:

$$Var(S') = \frac{n(n-1)(2n+5) - \sum_{i=1}^{P}(t_i - 1)(2t_i + 5)}{18} \tag{10}$$

n is the number of data points, P is the number of connection group and t_i is the number of data values in group P. If there is no binding group, this process can be ignored (Kisi & Ay 2014).

$$Z = \begin{cases} \dfrac{S'-1}{\sqrt{Var(S')}} & S' > 0 \\ 0 & S' = 0 \\ \dfrac{S'+1}{\sqrt{Var(S')}} & S' < 0 \end{cases} \tag{11}$$

$Z > 0$ indicates an increasing trend while $Z < 0$ shows a decreasing trend. Moreover, Sen's slope was also used to estimate the slope of trend. The residual variance formula in the Mann-Kendall test can be expressed as (Silva *et al.* 2015):

$$Q_i = \frac{X_j - X_k}{j - k} \tag{12}$$

where X_j and X_k are the data values of a time series. The way to calculate Sen's slope, is as follows (Silva *et al.* 2015):

$$Q_{med} = Median(Q_i) \tag{13}$$

A positive value of Q_{med} indicates an increasing trend, and a negative value indicates a decreasing trend. The greater the absolute value of Q_{med}, the greater the rising or falling trend (Wang *et al.* 2016). In this study, a 30-year window is first used to calculate the indices reflecting the temporal distribution of precipitation. The time series for each grid (station) was then prewritten and used to calculate Sen's slope. A 5% significance level was applied in the trend detection.

RESULTS

General features of precipitation changes

Figure 2 shows the trends of WD, median and Q95 of precipitation over China during the period of 1961–2013.

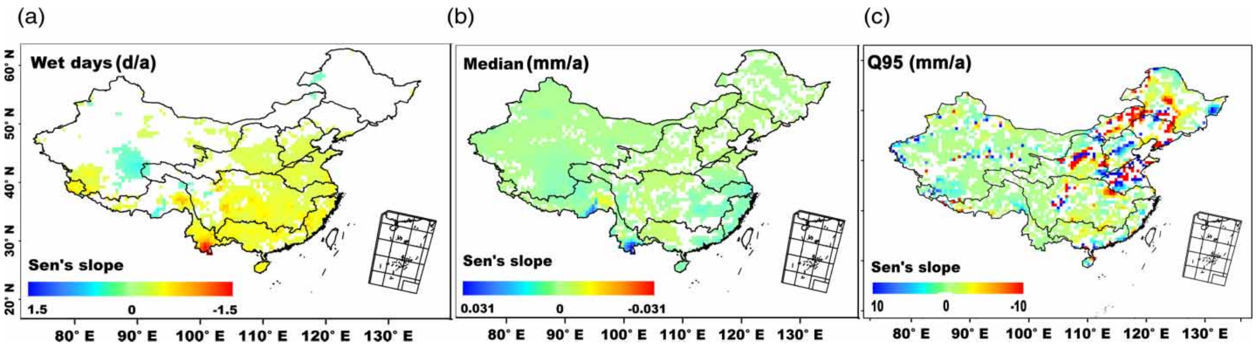

Figure 2 | Spatial distribution of Sen's slope in (a) wet days, (b) median and (c) Q95 of precipitation over China from 1961 to 2013. The grids displayed with color show the changes are statistical significant at 0.05 level. Please refer to the online version of this paper to see this figure in color: http://dx.doi.10.2166/nh.2017.083.

Significant increase (mainly located in central and southern China) and decrease (mostly located in northwestern China) in WD can be found in 3.7% and 36.5% of the grids ($p < 0.05$), respectively. For the median of daily precipitation, 53.6% of the total grids are characterized by a significant increasing trend while only 20.8% grids show a significant decreasing trend (mostly located in southwestern China). Significant increases and decreases in the Q95 of precipitation are found in 33.9% and 28.8% of the grids, which are mainly distributed in eastern and northern China, respectively (Figure 2(c)).

The averaged trends of WD, median and Q95 of precipitation are also shown for 10 major basins over China in Figure 3. We can observe a decreasing trend in WD for all basins, for example, the Pearl River basin exhibits the maximum rate of declining (−0.39 mm/a) while the Songhua River basin shows the minimum decreasing rate (−0.02 mm/a). For the median of daily precipitation, all basins show increasing trends except for Liaohe basin, Haihe basin and Yellow River basin with the largest increasing rate in Southeast River basins. Moreover, the Q95 of precipitation shows decreasing trends in Southeast River basin, Pearl River basin and Southwest River basin while exhibits increasing trends in other basins, especially in Huaihe basin (Figure 3(c)). The median and Q95 of precipitation overall increased, associated with decreased WD in most parts of China during the period of 1961–2013.

Changes in temporal inequality of daily precipitation

Figure 4 shows the trends of Gini coefficient (G) and Lorenz asymmetry coefficient (LAC) over China during the past 53 years. Significant increase (e.g., Xinjiang province) and decrease (e.g., some parts in southwestern China, central and northeastern China) in G can be found in 43% and 25% of the total grids over China, respectively. This result indicates an increasing trend of temporal inequality of daily precipitation in most regions of China. In addition, sporadically significant trends (increase in 8.5% while decrease in 3.3% of total grids) in LAC are found over China during the period 1961–2013 (Figure 4). However, we can find that the majority of the pronounced increasing

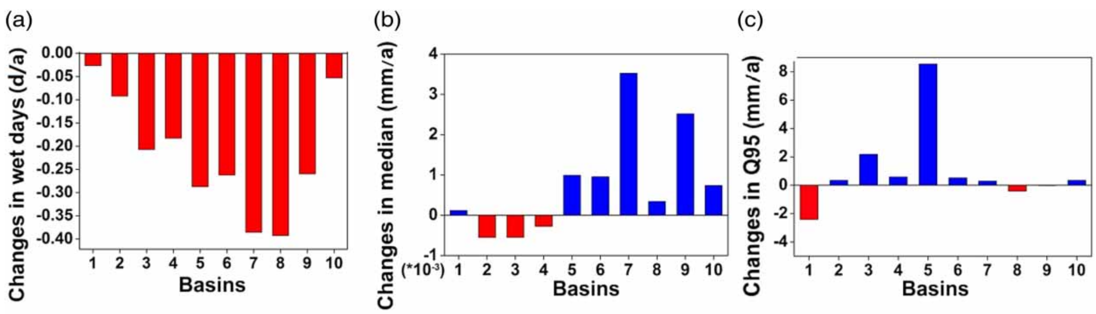

Figure 3 | Averaged trends of (a) wet days, (b) median and (c) Q95 in 10 major basins over China during 1961–2013.

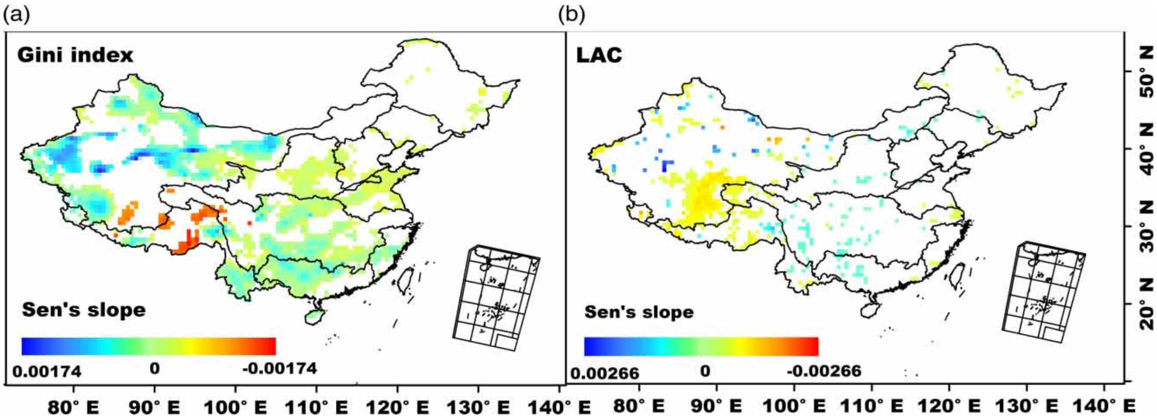

Figure 4 | Spatial distribution of Sen's slope in (a) Gini index, (b) Lorenz asymmetry coefficient of daily precipitation over China from 1961 to 2013. The grids displayed with color show the changes are statistical significant at 0.05 level. Please refer to the online version of this paper to see this figure in color: http://dx.doi.10.2166/nh.2017.083.

trends are observed in Xinjiang province while the majority of significant decreasing trends are located in the southwest of China and the south of northwestern river basins. The differences between trends in Gini coefficient and Lorenz asymmetry coefficient indicate that the reasons for the changes in temporal inequality of daily precipitation are regionally varied over China.

The averaged trends of G and LAC in 10 major basins are also shown in Figure 5. We can observe an increasing trend of G in all basins with maximum increasing rate found in the Pearl River basin and minimum one in Liaohe basin (Figure 5). The LAC shows an increasing trend in all basins over China except for Songhua River basin, Southeast River basin and Southwest River basin, with the most significant increasing trend occurs in Haihe basin. There are mainly two patterns for the changes in temporal inequality of daily precipitation over China. The first pattern is that both G and LAC increase, indicating that the observed increase in precipitation inequality is mainly caused by the increase in heavy rainfall events. This pattern features in most areas in China. Another one is characterized by increased G associated with decreased G, which means that the observed increase in precipitation inequality is mainly caused by a great deal of light rain events. This pattern is only observed in Songhua River basin, Southeast River basin and Southwest River basins. Our results overall support the previous global-scale study using climate models (Lau *et al.* 2013), which showed that the intensity of extreme precipitation events will increase by $7 \pm 2.4\%{}^{\circ}C^{-1}$ while that of medium-sized precipitation events will decrease by $2.5 \pm 0.6\%{}^{\circ}C^{-1}$ under a scenario of 1% increase per year of CO_2 emission. The observed decrease in WD over China during the period 1961–2013, is also in agreement with that found in Lau *et al.* (2013) and Rajah *et al.* (2014).

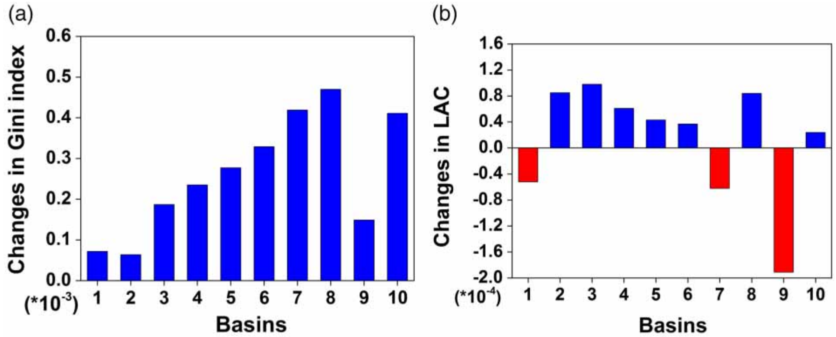

Figure 5 | Averaged trend in (a) Gini index, (b) Lorenz asymmetry coefficient of daily precipitation in 10 major basins over China.

Changes in dry spell and wet spell over China

The changes in wet and dry persistence revealed by *P*00 and *P*11 over China during the period of 1961–2013 are exhibited in Figure 6. The *P*00 shows increasing trends in all grids with 63% of them significant. The most pronounced increasing trends can be found in the southwestern China, Yangtze River basin and the northwest part of Tibetan Plateau. Moreover, negative trend of *P*11 can be found in the majority of grids (about 91.2%), especially in central and northeastern China while the positive trend can be found in the North China Plain and the southern parts of the Tibetan Plateau and Xinjiang province. We also show the averaged trends of *P*00 and *P*11 in 10 major basins during the past 53 years over China (Figure 7). The *P*00 (*P*11) shows an increasing (decrease) trend but varies among all basins. The most significant (insignificant) downward trend in *P*11 can be found in Southeast River basin (Haihe basin). These results obtained can therefore indicate that the dry persistence is increasing while the wet persistence is decreasing, which implies increasing risk of drought and flood over China.

Droughts and floods are not only related to the total amount of precipitation but are also closely related to the temporal distribution of precipitation (Deng *et al.* 2014). This study shows that the temporal inequality of precipitation increased associated with ascending heavy rain and decreased *P*11 (and thus increased *P*00), which indicates that the potential risks of regional droughts and floods would increase over China. The results obtained are consistent with Liu *et al.* (2016) and Li *et al.* (2014). At the regional scale, a decreasing (increasing) trend in the median of precipitation (*P*00) is observed in the Liaohe, Haihe and Yellow River basins. The result is in agreement with that

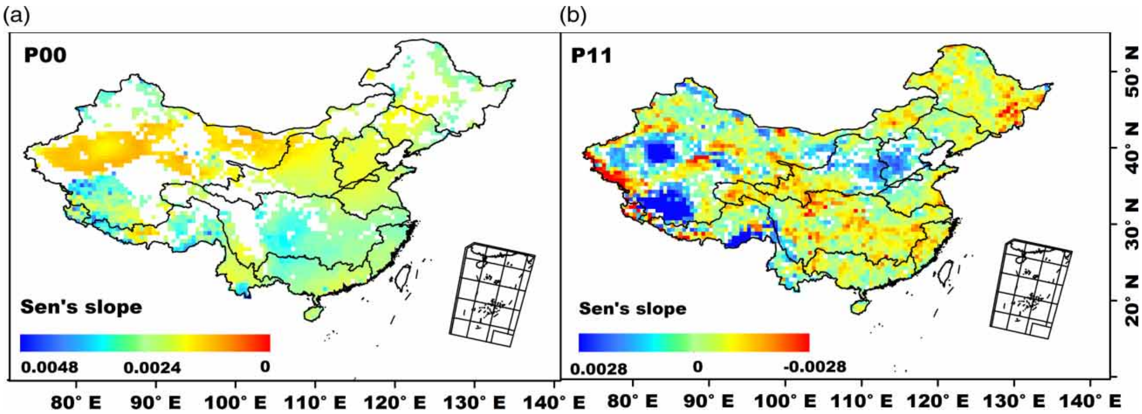

Figure 6 | Spatial distribution of Sen's slope in (a) *P*00 and (b) *P*11 of daily precipitation over China during 1961–2013. The grids displayed with color show the changes are statistically significant at 0.05 level. Please refer to the online version of this paper to see this figure in color: http://dx.doi.10.2166/nh.2017.083.

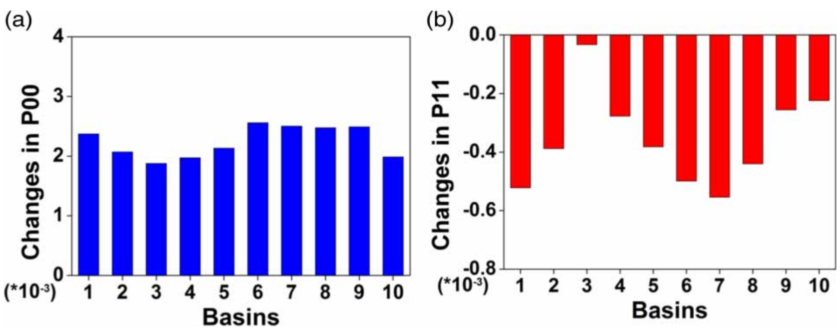

Figure 7 | Averaged trend in (a) *P*00 and (b) *P*11 in 10 major basins over China during 1961–2013.

Table 1 | Averaged Pearson coefficients between different indices used in this study

Indices	WD	G	S	Median	Q95	P00	P11
WD	1.00	−0.59	−0.46	−0.55	−0.31	−0.52	0.24
G	−0.59	1.00	0.19	0.39	0.13	0.27	−0.19
S	0.05	0.19	1.00	−0.73*	0.25	−0.55	0.20
Median	−0.55	0.39	−0.73*	1.00	0.06	−0.65*	−0.40
Q95	−0.31	0.13	0.25	0.06	1.00	−0.32	0.25
P00	−0.52	0.27	−0.55	−0.65*	−0.32	1.00	−0.73*
P11	0.24	−0.19	0.20	−0.40	0.25	−0.73*	1.00

*Correlation is significant at 0.05 level.

showed in Yang *et al.* (2016), in which a drying trend has been reported in most parts of Haihe basin.

Dependence analysis of indices

The Pearson coefficient was used to examine the correlations among the indices used in this study, i.e., WD, *G*, *LAC*, *P*00 and *P*11, median and Q95 of daily precipitation (Table 1). Overall, *G* is positively correlated to *LAC*, *P*00 and the median and Q95 of daily precipitation, while negatively correlated with WD and *P*11. *LAC* is positively correlated to *G*, *P*11 and the Q95 of daily precipitation while negatively correlated with WD, *P*00 and the median of precipitation (significant) over China during the period 1963–2013. Besides *G* and *LAC,* the extreme precipitation revealed by the Q95 of daily precipitation is positively correlated to *P*11 and the median of daily precipitation. In general, *LAC*, *P*00 and *P*11 have a high degree of association with median precipitation while *G* has a high dependence with WD.

CONCLUSIONS

In this study, the temporal inequality and persistence of precipitation across China are comprehensively investigated based on the gridded daily precipitation data during the period 1961–2013. The conclusions can be given as follows.

In most parts of China, the number of WD decreased while the median and Q95 of precipitation increased during the past 53 years. Also, the change in temporal inequality of daily precipitation over China can be summarized into two patterns: one dominant pattern is that both *G* and *LAC* increased which can be detected in most of major basins (7 out of 10). Another one is characterized by the increased *G* and declined *LAC*, which is only featured in Songhua river basin, Southeast river basin as well as Southwest river basin. Finally, the persistence analysis shows that the dry spell increased while wet spell decreased across China which indicates the potential risks of drought is increasing under a changing climate.

ACKNOWLEDGEMENTS

This research was financially supported by the National Key Research and Development Program of China (2016YFC0401401 and 2016YFA0602402), the National Natural Science Foundation of China (41401037, 41501027 and 41330529) and the Key Research Program of the Chinese Academy of Sciences (ZDRW-ZS-2017-3-1). We thank the editors and reviewers for their invaluable comments and suggestions.

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First received 25 April 2017; accepted in revised form 9 August 2017. Available online 27 November 2017