Development of the homogenized monthly precipitation series during 1910–2014 and its changes in Hunan Province, China

Jiadong Peng, Yufang Liao, Yuanhua Jiang, Jianming Zhang and Xingren Qi

ABSTRACT

Based on the statistical method and the historical evolution of meteorological stations, the precipitation time series for each station in Hunan Province of China during 1910–2014 are tested for their homogeneity and then adjusted. The missing data caused by war and other reasons at the eight meteorological stations which had records before 1950 is filled by interpolation using adjacent observations, and complete precipitation time series since the establishment of stations are constructed. After that, according to the representative analysis of each station in different time periods, the precipitation series of Hunan Province during 1910–2014 are built and changes are analyzed. The results indicate that the annual precipitation has no significant linear trend but has obvious inter-decadal fluctuation during 1910–2014 and a periodic oscillation of 20 years is the most significant. Precipitation in winter (DJF) and summer (JJA) shows a slight wetter trend, and a slight dryer trend in spring (MAM) and autumn (SON). Abrupt change test suggests that annual and seasonal precipitations except for MAM and SON have abrupt ascending changes in the recent 100 years.

Key words | homogeneity, Hunan Province of China, interpolation, precipitation series, temporal variation

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INTRODUCTION

Precipitation is one of the most important climatic variables. First, as one of the most important indices to climatic change, precipitation change is the result and reflection of the changes of many other climatic factors. Second, it has a direct influence on industrial and agricultural production. Drought and flood caused by abnormal precipitation always lead to great loss to the national economy. Thus, the change, especially the long-term change of precipitation, has attracted more and more attention from climatologists (Bradley *et al.* 1987; Tu 1987; Diaz *et al.* 1989; Legates & Willmott 1990; Vinnikov *et al.* 1990; Dai 1997; Ye 1998; Li & Tu 2000, 2002; New *et al.* 2000; Chen *et al.* 2002; Shi & Chen 2002; Wang *et al.* 2002; Wen *et al.* 2006).

In recent years, the compilation and construction of long-term and homogeneous precipitation datasets have been ongoing processes throughout China (Li *et al.* 2012), but at regional scale, long-term and homogeneous precipitation data are still lacking. Although some researchers have constructed several precipitation series of centennial scale in different regions of China (Zhou & Yang 2001; Huang *et al.* 2007; Jiang *et al.* 2009), these series were developed without considering homogeneity due to inconsistent observational schedules in different years, relocations of stations, and missed observations (Wu 2007). Lying in the conjunction zone between the east and west of China and being located in the lower reaches of the southern margin of the Qinghai-Tibet Plateau and the southern part of the middle reaches of the Yangtze River (shown in Figure 1), Hunan Province is surrounded by mountains on three sides (shown in Figure 2); no work has been done on

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Figure 1 | Location of Hunan Province in China.

construction of a long time-scale precipitation series in such a particular position. Therefore, in order to better explain the regional characteristics of long-term precipitation changes, it is necessary to further reconstruct the homogeneous precipitation series in Hunan over the past 100 years, particularly given that the precipitation data before 1950 are incomplete due to war and other reasons in this region and the inhomogeneity problems of the precipitation data in China (Li *et al.* 2003, 2008; Liu & Li 2003; Jiang *et al.* 2008).

In this paper, we systematically adjust the homogeneity of the historic precipitation observations, and fill in the missing data of each station with a regression model based on the adjacent stations' data. After that, the complete series of each station since establishment is built up. Then, a representative analysis of each station's precipitation series is carried out in order to choose appropriate representative stations for different time periods. Based on the above steps, Hunan's regional precipitation series of the past 100 years is constructed and the change characteristics are analyzed.

MATERIALS

The raw data used in this paper comprise three parts: First is the monthly precipitation data of eight meteorological stations before 1950 from Hunan Provincial Meteorological Archives (the geographical distribution shown in Figure 2(a)). The precipitation observation of Changsha and Yueyang Station began in 1909 and the other six stations began during 1932–1942; due to war and other reasons, each station had several missing records at some stages (shown in Table 1). Second is the monthly precipitation data of 96 meteorological stations in Hunan Province since 1951 (the geographical distribution shown in Figure 2(b)). Third is the monthly precipitation data of Wuhan, Nanjing, Hangzhou, Chongqing, and Guangzhou from NMIC (National Meteorological Information Center). These data are treated and selected as the reference data for the homogeneity test of the long time

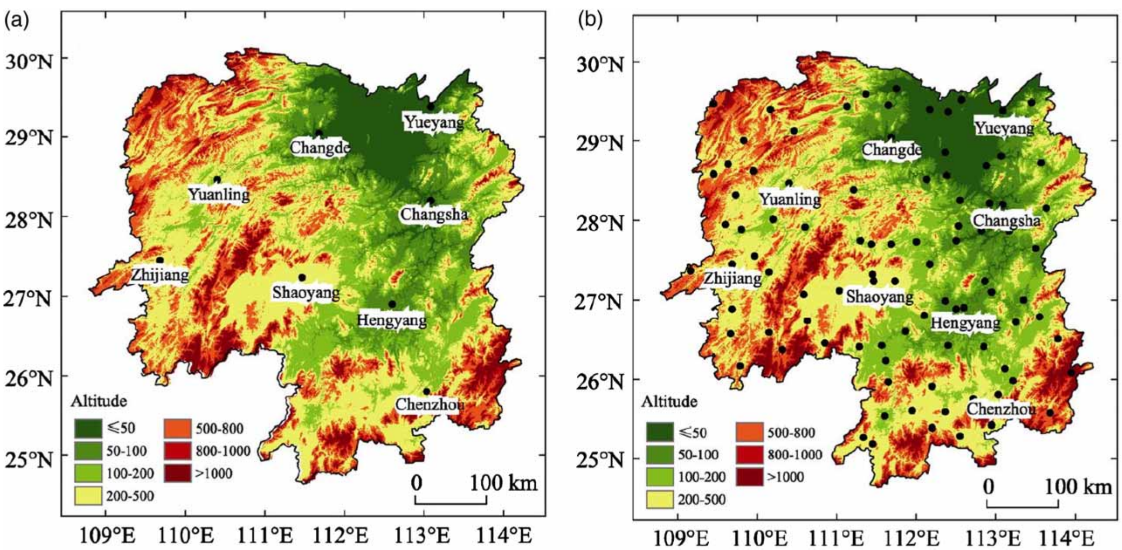

Figure 2 | Geographical distribution of the observation stations: (a) stations with data before 1950, (b) all the stations after 1951.

Table 1 | Information for eight meteorological stations with data before 1950 in Hunan Province

Station no.	Station name	Starting time (month/year)	Missing periods in record (month/year)	Missing number of months
57,584	Yueyang	12/1909	01/1918 07/1921 09/1928 10/1931 07/1934 05/1938–12/1950	157
57,655	Yuanling	07/1942	02/1949–12/1950	23
57,662	Changde	08/1932	12/1934 11/1938–03/1946 06/1949–12/1949 07/1950	98
57,679	Changsha	06/1909	04/1910–09/1910 01/1918 11/1938–03/1939 01/1941–03/1946 05/1949–09/1949	80
57,745	Zhijiang	01/1937	01/1938–05/1938 09/1949–05/1950	14
57,766	Shaoyang	09/1936	06/1944–09/1950	76
57,872	Hengyang	01/1933	11/1938–10/1939 10/1941 01/1944–06/1946 01/1948–01/1950	68
57,972	Chenzhou	12/1936	11/1943 06/1944–07/1946 08/1949–12/1950	44

station precipitation series (mainly for Changsha and Yueyang) in Hunan Province.

CONSTRUCTION OF PRECIPITATION SERIES

Homogeneity test and adjustment

The reliability and the accuracy of climate data are the basis of climate change research. Change of observation instrument, station relocation, and other reasons would affect the homogeneity of the observation data (Li *et al.* 2003). Therefore, the homogeneity test and adjustment to the precipitation series of each station is a prerequisite of analyzing the precipitation changes.

To carry out the homogeneity test in precipitation series of a station, it is very important to construct a reasonable reference series by using the data of the adjacent stations, because the reference series is an important indicator of local climate and any significant difference from the local climate signal would be assumed to be discontinuity (Li *et al.* 2003). The number of meteorological stations in Hunan was relatively few before 1950 and has increased significantly since 1951. In order to ensure the nearest station is chosen to construct the reference series, the homogeneity test and adjustment in this paper are divided into two parts: First, the homogeneity test and adjustment is carried out for the precipitation series of all 96 stations during 1951–2014 by using the adjacent stations in Hunan as the reference. Second, a similar procedure is carried out for the series of eight stations during 1910–1950 by using both the adjacent stations in Hunan and other stations in surrounding provinces as reference.

The homogeneity of the annual precipitation series of all 96 stations during 1951–2014 in Hunan has been tested with the two-phase regression model (Lund & Reeves 2002) and the preliminary discontinuities in these time series obtained.

Table 2 | Break points of precipitation series during 1951–2014 and relocation time at meteorological stations in Hunan Province

Station no.	Station name	Break points	Relocation time (day/month/year)
57,687	Wangchengpo	1974	01/07/1975
57,981	Zixing	1992	01/01/1993
59,063	Jianghua	1989	01/01/1990

Likewise, the time series of precipitation at monthly scale has also been tested with the same method and the potential discontinuities also obtained. Then, the common inhomogeneous points are found by comparison of preliminary and potential discontinuities. Based on the above two steps, the manual analysis of the difference images between each station's series and those of surrounding stations is carried out, taking the stations' historical evolution into consideration. Finally, it is confirmed that, among the 96 stations, the precipitation series at three stations are inhomogeneous with a total of three break points (shown in Table 2). According to the above results, all of the inhomogeneous series are adjusted.

As an example, Figure 3 shows the differences of Zixing station's series before and after adjustment. The series before 1992 shows distinct inhomogeneity, while the linear trend of both the original series and the adjusted series exhibits great differences. Before adjustment, precipitation increasing rate is 73.3 mm/decade, while after adjustment it becomes only 32.3 mm/decade. Obviously, the adjusted annual precipitation series demonstrates a smaller secular trend, which is more reasonable than those of adjacent stations. Similar methods are also applied to the rest of the station series for the purpose of homogeneity.

Figure 4 shows the difference of the linear trend between the original annual precipitation and that of the adjusted version. It is noticeable that the linear tendency rates in several stations are much higher or lower than adjacent stations before being homogenized, and after being homogenized, the difference becomes smaller. This indicates that the linear tendency rate of homogenized precipitation can reflect the local climate change of the station area accurately.

The method of the homogeneity test for the precipitation series of eight stations in Hunan Province during 1910–1950 is basically the same as the above method, and the only difference is which stations are selected as the reference series. In view of the fact that there are only two stations (Changsha and Yueyang) that have over 100 years' series in Hunan, no adjacent station in Hunan can be chosen to be treated as a reference station for the homogeneity test of the above two stations. Thus, several stations in surrounding provinces like Wuhan, Guangzhou, etc. from NIMC were selected to construct the reference series of Changsha and Yueyang. For the other six stations which began records during 1932–1942, adjacent stations in Hunan are selected as reference stations for the homogeneity test. Finally, the result shows that no stations' precipitation series have confirmed inhomogeneity.

Interpolation for filling missing data before 1950

Eight meteorological stations have precipitation records before 1950 in Hunan Province, but some of the data in a

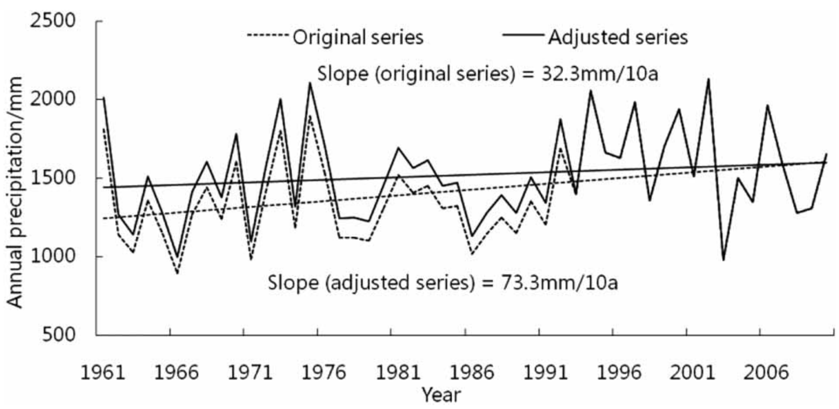

Figure 3 | The original and adjusted annual precipitation series in Zixing (57,981) during 1961–2010.

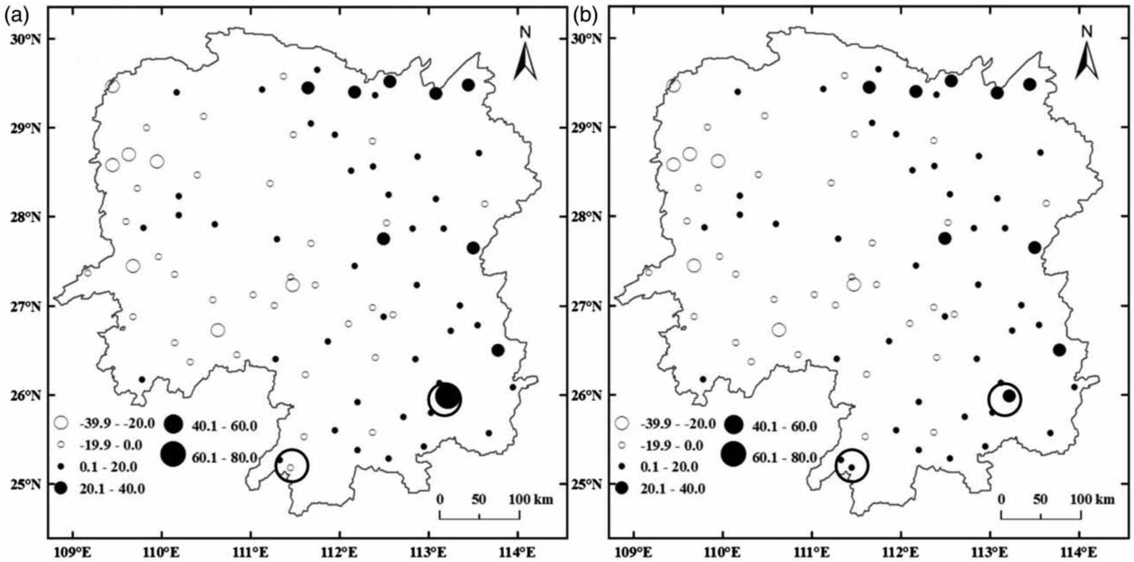

Figure 4 | Distribution of the linear tendency of annual precipitation during 1961–2010 in Hunan Province: (a) before homogenization, (b) after homogenization. Units: mm/decade. '○' denotes the stations in which linear tendency rates are significantly higher or lower than adjacent stations before homogenization.

few years were missing or incomplete due to war and other reasons. For this reason, the following method was used to carry out the interpolation to fill in the missing data. An adjacent station in Hunan which has the best correlation with the target station was selected as a reference station and a regression equation for reference and target stations was built using each month's precipitation series after being homogenized, thus the missing data of all eight stations were filled with interpolation month by month. Due to the different urbanization process since 1990 in Hunan and the difference of precipitation change rates caused by that, the above equations only use the precipitation data before 1990. All the equations are based on monthly data and are significant at the 0.05 level. Values of year and season were computed by the interpolated value of each month.

Taking the annual precipitation series of Changsha as an example for the assessment of interpolation, Figure 5 shows the differences of Changsha station's original and interpolated series. The two series are highly correlated and correlation coefficient reaches 0.710, linear trend analysis shows both a slightly downward trend in the two series, T-test and F-test show there is no significant difference between the mean and the variance of the two series. However, it should be pointed out here that the spatial variability of precipitation is larger compared with temperature, especially in Hunan Province with its complex terrain.

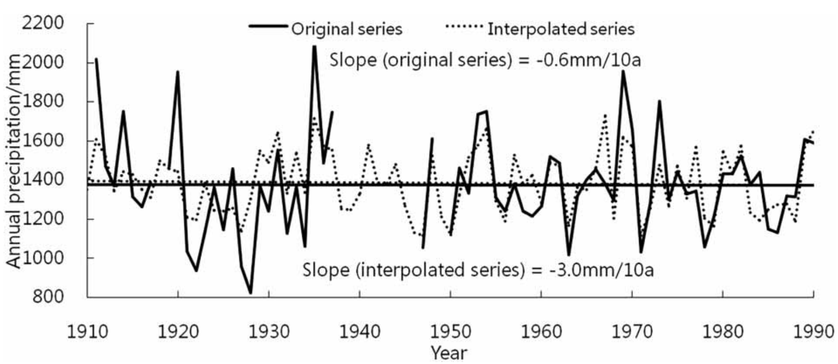

Figure 5 | The original and interpolated annual precipitation series in Changsha during 1910–1990.

Therefore, the interpolation of precipitation produces a greater error, especially in the abnormal and extreme years.

Construction of precipitation series during 1910–2014

The number of meteorological stations in Hunan changes from time to time. Only two stations (Changsha and Yueyang) had precipitation records during 1910–1931, and the other six stations began to produce meteorological observations one after another during 1932–1942 (shown in Table 1). The number of stations was maintained at eight during 1943–1950, then increased rapidly from 1951 to 1960 and remained stable since 1961. Under this situation, correlation analysis was used to find out the best representative stations (that is, the higher the correlation coefficient with the average of all 96 stations, the better the representation), and based on the above analysis and taking geographical distribution into account, as many as possible representative stations were selected to construct the precipitation series of Hunan Province during 1910–2014.

Results of correlation analysis show that the correlation coefficient with the average of all 96 stations and the average of the two stations, Changsha and Yueyang, is higher than Yueyang and Changsha separately. That means representation of the average of the above two stations' precipitation series (hereinafter referred to as two stations) is better than Yueyang and Changsha (shown in Table 3). Therefore, the precipitation series of Hunan Province during 1910–1936 is constructed based on the two stations. Due to the uniform geographical distribution of the eight stations which had precipitation records before 1950 and their good representation, the precipitation series of Hunan Province during 1937–1960 were constructed based on the average of the above eight stations (hereinafter referred to as eight stations), and precipitation series during 1961–2014 were calculated by the average of all 96 stations (hereinafter referred to as 96 stations). Based on the above steps, the regression models for two stations with 96 stations and eight stations with 96 stations were established to extend the series of 96 stations to 1910, month by month, and the monthly precipitation series of Hunan Province during 1910–2014 were constructed.

Figure 6 shows the average annual precipitation series of two stations, eight stations, and 96 stations. The mean precipitation of two stations and eight stations are highly correlated with 96 stations and the correlation coefficients are 0.760 and 0.944, respectively. Obviously, the 105 years series of 96 stations extended by two stations and eight stations is reasonable and reliable.

Table 3 | Correlation coefficient of monthly precipitation in Changsha and Yueyang, and their mean values with the average of 96 stations from 1961 to 1990

	1	2	3	4	5	6	7	8	9	10	11	12
Changsha	0.947	0.900	0.776	0.691	0.679	0.577	0.630	0.850	0.731	0.900	0.895	0.900
Yueyang	0.744	0.660	0.608	0.608	0.591	0.576	0.611	0.778	0.766	0.688	0.745	0.741
Average of 2 stations	0.922	0.867	0.811	0.702	0.721	0.691	0.721	0.880	0.859	0.879	0.887	0.892

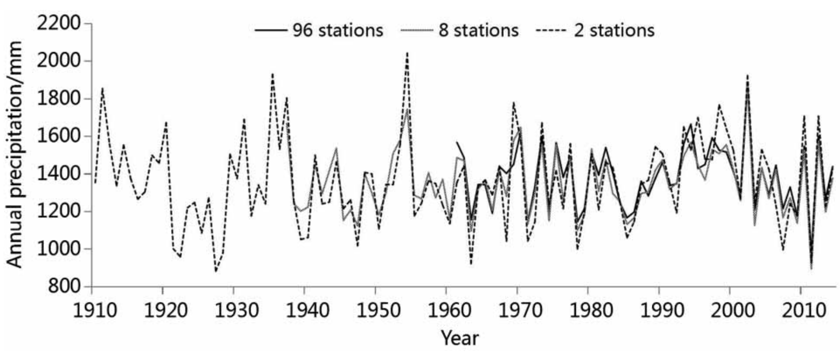

Figure 6 | The average annual precipitation series of two stations, eight stations, and 96 stations during 1910–2014.

ANALYSIS OF PRECIPITATION CHANGES

Changes in annual precipitation

The annual precipitation shows no significant linear trend in Hunan Province during 1910–2014 (shown in Figure 7(a)), and has an obvious inter-decadal fluctuation of a 20 years' period. Above normal precipitation appeared in the 1910s, 1930s, 1950s, and 1990s in accordance with below normal in the 1920s, 1940s, 1960s, 1980s, and 2000s. The maximum annual precipitation since 1910 was in 2002 in Hunan Province, with a total of 1,884.3 mm, and the minimum was in 2011 with a total of 974.8 mm.

Comparison of the reconstructed series with others (Figure 7(b) and 7(c)) demonstrated that the reconstruction matched well with the observed precipitation in Eastern China and the whole of China, especially for the decadal variations, and for inter-annual variations, the difference

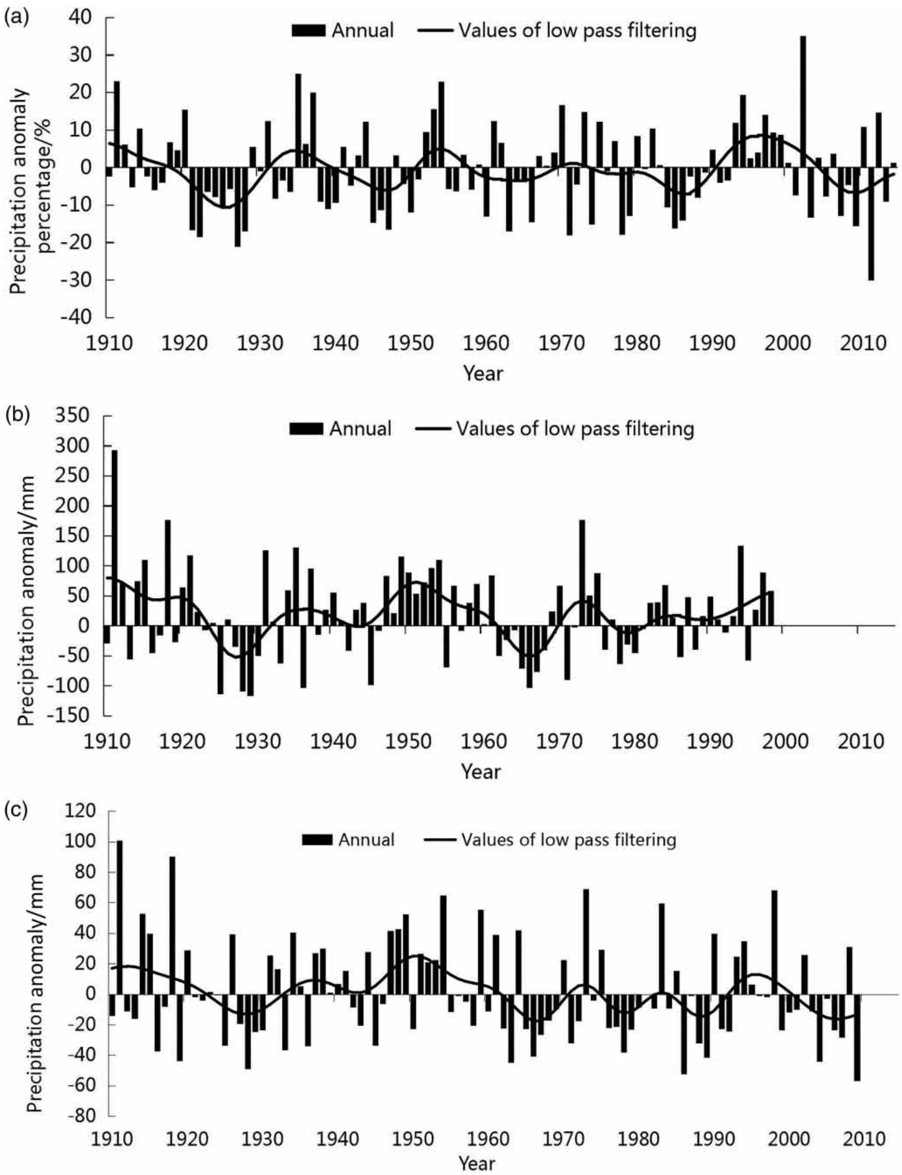

Figure 7 | Annual precipitation anomaly percentages during 1910–2014 in Hunan Province and comparison with other series: (a) annual precipitation reconstruction, (b) Eastern China annual precipitation anomalies during 1910–1998 (Wang et al. 2000), (c) China annual precipitation anomalies during 1910–2009 (Li et al. 2012).

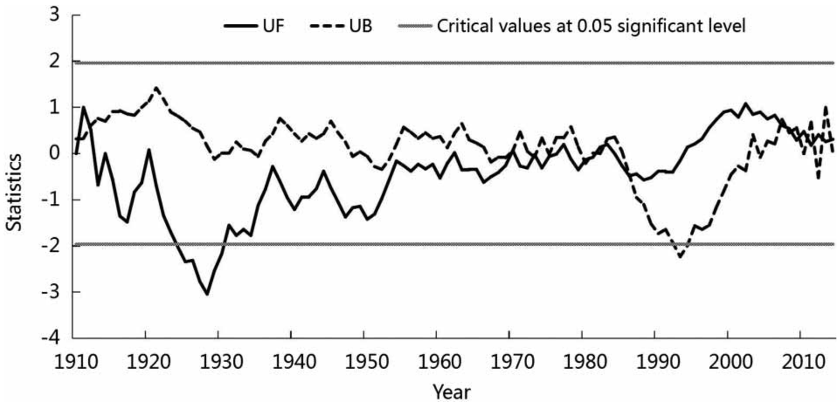

Figure 8 | Mann–Kendall abrupt change test of annual precipitation during 1910–2014 in Hunan Province.

became larger especially from the late 1940s to the early 1950s and the whole of the 1980s.

The Mann–Kendall abrupt change test (Wei 2007) of annual precipitation during 1910–2014 in Hunan Province shows that the annual precipitation presented a fluctuation change in the past 100 years and had a significant abrupt ascending point in the middle and late 1980s. According to the intersection of the UF and UB curve, the abrupt change point is determined for the year of 1987 (shown in Figure 8). The result of Morlet wavelet transformation (Wei 2007) indicates that the short period oscillation is mainly a periodic wave of 2–3 and 6–8 years, and a 20-year period oscillation was maintained in the past 100 years. In addition, there is a long periodic oscillation of 40 years maintained during 1910–2014 (shown in Figure 9).

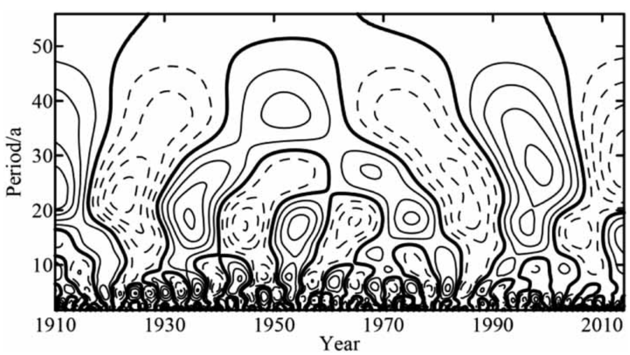

Figure 9 | Morlet wavelet transformation of annual precipitation during 1910–2014 in Hunan Province.

Changes in seasonal precipitation

The precipitation series of the four seasons show no significant linear trend during 1910–2014 (shown in Table 4). They were mainly dominated by relatively less precipitation in DJF before the 1980s and became greater in the 1990s and then converted to less from the early 2000s to the present (shown in Figure 10(a)). Abrupt change test shows that there is a significant ascending point in the year of 1978. In MAM, there are three obvious abundant and deficient periods: the abundant are the 1930s, 1950s, and 1970s, and the deficient are the 1940s, 1980s, and 2000s (shown in Figure 10(b)). There is no significant abrupt ascending or descending point in MAM during the last 100 years. In JJA, there are two obvious abundant and three deficient periods: the abundant are the 1910s and 1990s, and the deficient are the 1920s, from the middle 1940s to the late 1960s and 1980s (shown in Figure 10(c)). There is a significant abrupt ascending point in the year of 1992. In SON, from the early 1910s to the early 1920s is an obvious abundant period. Since then, the precipitation shows fluctuation until the present and has no obvious abundant or deficient

Table 4 | Seasonal precipitation linear tendency rates (unit: mm/decade) and correlation coefficient of linear trend and precipitation series during 1910–2014 in Hunan Province

	DJF	MAM	JJA	SON
Linear tendency rate	2.6	−0.1	1.7	−2.9
Correlation coefficient	0.1652	0.0044	0.0529	0.1100

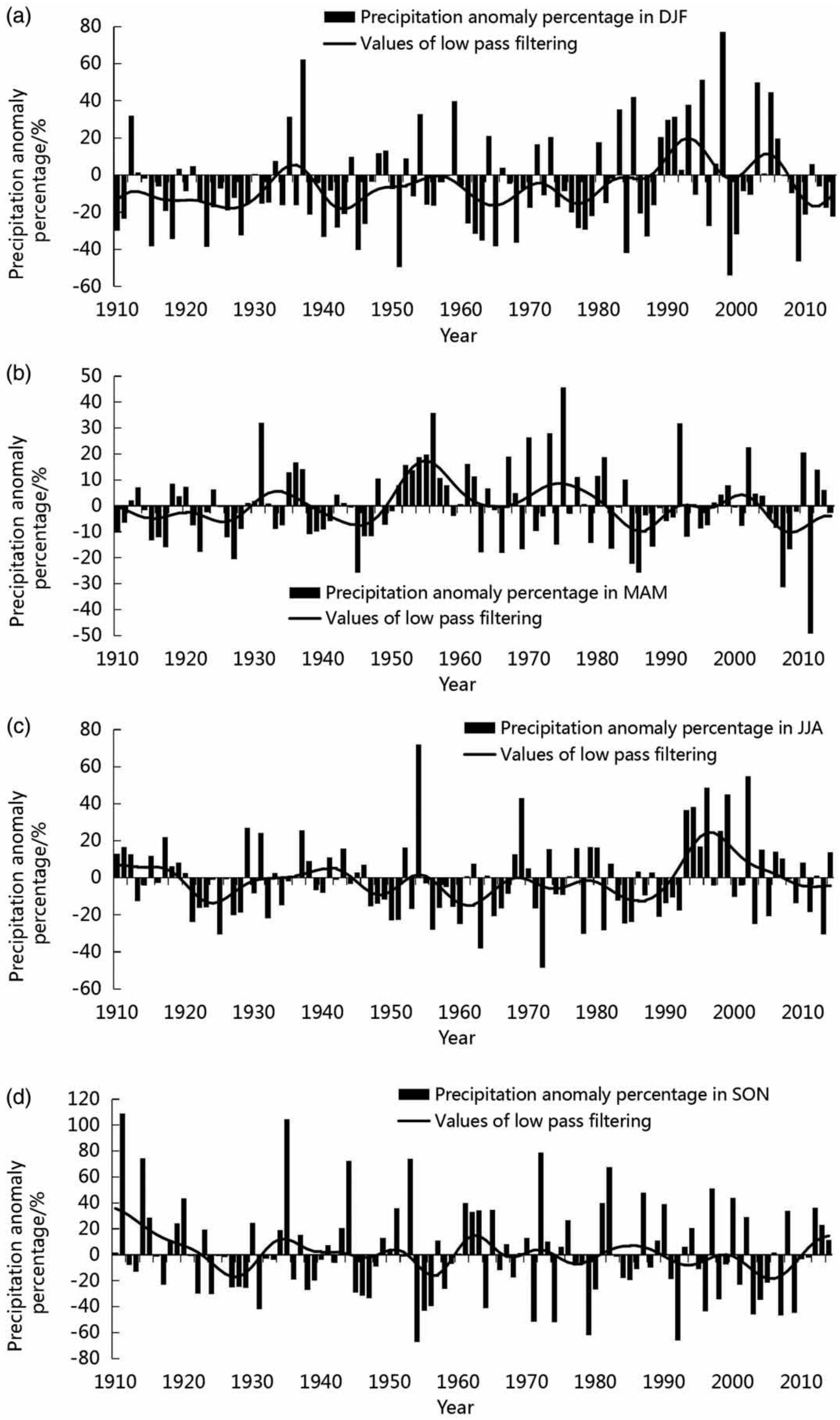

Figure 10 | The precipitation anomaly percentages in (a) DJF, (b) MAM, (c) JJA, and (d) SON during 1910–2014 over Hunan Province (to average level of 1971–2000).

period (shown in Figure 10(d)). There is no significant abrupt ascending or descending point in SON.

DISCUSSION AND CONCLUSIONS

1. Construction of long-term homogeneous time series is essential for research on climate change. Based on the technique of two-phase regression and the historical evolution of meteorological stations, the precipitation time series for each station in Hunan Province during 1910–2014 were tested for their homogeneity and part of the precipitation series were adjusted for inhomogeneity. After using interpolation and representative analysis in this study, we objectively established a set of homogenized monthly precipitation series in Hunan Province back to the early 19th century.
2. The annual precipitation of Hunan Province shows no significant linear trend during 1910–2014, but has obvious inter-decadal fluctuation. The result of Morlet wavelet transformation shows that the annual precipitation series have one long periodic oscillation of 40 years and one intermediate frequency oscillation of 20 years and several high frequency oscillations.
3. The change of precipitation in Hunan Province demonstrates a seasonal difference. Precipitation in DJF and JJA shows a slight wetter trend during the past 100 years, and a slight dryer trend in MAM and SON. Interdecadal variability of seasonal precipitation is significant and there are one or more pluvial (dry) periods for all four seasons during 1910–2014.
4. Abrupt change test shows that the annual precipitation and precipitation in DJF and JJA all have a significant abrupt ascending point during the past 100 years, and the time of sudden change for DJF precipitation is the earliest, then for the annual, and the precipitation in JJA is the latest. No abrupt ascending or descending point was found in MAM and SON.
5. It should be pointed out that the spatial variability of precipitation is larger compared with temperature, and considering the complex terrain of Hunan Province, the interpolation of precipitation produces bigger error, especially in the abnormal and extreme years, and there may be a considerable difference between the interpolation results and the actual situation. The inadequate spatial and temporal representativeness of precipitation makes the precipitation variation series built up in this paper an approximate estimation needing further research and development.

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