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Changing characteristics of precipitation during 1960–2012 in Inner Mongolia, northern China

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Abstract Based on daily precipitation records at 46 meteorological stations in Inner Mongolia, northern China, the space and time changes in precipitation characteristics are analyzed by defining 15 precipitation indices. The Mann–Kendall trend test is used to detect trends in the precipitation indices series. Results indicate that: (1) Inner Mongolia is dominated by decreasing precipitation, and precipitation deficit may further deteriorate the shortage of water resources; (2) precipitation extremes are not dominant in this province, and most extreme precipitation indices are generally decreasing; (3) wet spells with short duration are prevalent in this province and the occurrence and fractional contribution of short-duration wet spells are increasing; (4) daily precipitation events with light and moderate intensity are dominant in this province and the occurrence and fractional contribution of moderate precipitation are increasing; (5) a higher risk of droughts can be expected in summer and precipitation in winter and spring is increasing, which imply evident seasonality and seasonal shifts of precipitation changes within this province.

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1 Introduction

Changes in climate may have already affected elements of the hydrologic cycle such as precipitation redistribution, snow accumulation and meltwater, evapotranspiration and the surface and subsurface water table (Liang et al. 2011). Precipitation is one of the most important variables in diagnosing climate change as well as revealing the eco-environmental response to climate change on a regional scale (Cannarozzo et al. 2006). Temporal and spatial variability of precipitation around the world is receiving increasing attention, because the information about changing patterns of precipitation is the starting point for accurate assessment of water resources, flood and drought control, understanding climate change and efficient water management (Wang et al. 2011). Recently, adopting precipitation-related indices of various aspects has been the main method to investigate the changing characteristics of precipitation (Bewket and Conway 2007; Santo et al. 2013; Huang et al. 2013).

Numerous studies on the amount and the days and intensity of precipitation have been undertaken all over the world. The main areas where decreasing trends have been observed are Greece, the Canadian Prairies, Bologna and the island of Sicily in Italy, western and southern Turkey

and the Indian Himalayas, while increasing trends in annual precipitation have been observed in the USA, eastern and northeastern Australia, South Africa and the UK (Wang et al. 2011). A significant decrease in the number of rainy days and a significant increase in the precipitation intensity values have been identified in many places in the world, such as China and America (Coscarelli and Caloiero2012). Extreme hydrological events related to precipitation and streamflow can cause large losses of human life and exponentially increasing costs associated with them (Karl and Easterling 1999). Thus, much attention has been paid to precipitation extremes at regional or national scales and various indicators, such as percentile-based indices, threshold indices, duration indices and absolute indices, have been widely used to describe their changes (Alexander et al. 2006). For example, a significant increasing trend in one or more characteristics of extreme precipitation, such as days with extreme precipitation, heavy precipitation events or intensity and frequency of extreme precipitation, have been confirmed in the USA, Bulgaria, central India, southern Africa and southern Brazil (Wang et al. 2013).

Additionally, the other aspects of characteristics of precipitation (e.g., consecutive precipitation events, intra-annual precipitation distribution) have also attracted more attention. In recent studies, the duration of consecutive precipitation events and related precipitation amount have aroused much interest (e.g., Zolina et al. 2010, 2012, 2014). Analyzing wet spells (WS) and the associated precipitation amount over Europe, Zolina et al. (2010) indicated that longer wet spells should have a significant impact on the terrestrial hydrologic cycle, including subsurface hydro-dynamics, surface runoff and European flooding. In the Pearl River basin, China, Zhang et al. (2012) found that the occurrence and fractional contribution of wet spells with longer durations are decreasing in recent decades and WS with shorter durations, e.g., 2–5 days are tending to be predominant in recent decades with increasing total precipitation amount. Different precipitation indices have been used to quantify intra-annual precipitation distribution and among these the precipitation concentration index (PCI) (Oliver 1980) is recommended, as it provides information on long-term total variability in the amount of rainfall received (De Luis et al. 2011). In Spain, significant increases in PCI are found mainly in the central Pyrenees and Ebro basin to the north-east and the Iberian range to the east inland and to the south-west (De Luis et al. 2011). With regard to China, positive trends in the PCI are found at most stations in the Jiangxi Province and the Huai River Basin (Huang et al. 2013; Shi et al. 2014).

In northern China, water resources shortage is one of the prominent limiting factors which hinders the economic and social development of the Inner Mongolia Autonomous Region. A better understanding of precipitation variability on a regional scale will assist in determining water management policies and also in planning sustainable agricultural practices. To our knowledge, however, most studies about precipitation in Inner Mongolia have focused on the changes of annual precipitation amount (Gao et al. 2009; Bao et al. 2011; Pei et al. 2011). Therefore, there are four key objectives of this paper: (1) to systematically investigate long-term trends of precipitation amount, rainy days and precipitation intensity using historically observed daily precipitation at different time scales (i.e., annual and seasonal); (2) to explore space and time variations of extreme precipitation using a selection of six extreme indices; (3) to understand the changing patterns of precipitation structure based on consecutive precipitation events and daily precipitation events; (4) to detect the changes of intra-annual precipitation distribution using the precipitation concentration index.

2 Study region and data

The Inner Mongolia Autonomous Region is located between 37°24′–53°23′N and 97°12′–126°04′E with a mean elevation of 1014 m. As the third largest among China's provinces and autonomous regions, it covers an area of 1.18 million km^2 or 12.3 % of the country's territory. Inner Mongolia, with a temperate continental monsoonal climate, has a cold and long winter with frequent blizzards and a warm and short summer. Except for the relatively humid Greater Hinggan Mountain area, the most part of Inner Mongolia is arid, semi-arid or semi-humid from west to east. It has an average annual temperature of −1 to 15 °C and an annual average precipitation of 30–500 mm. On the basis of the length of records, 51 stations that have 53-year records by 2012 were selected as candidate stations. The initial data set of daily precipitation amounts for the period 1960–2012 at the 51 candidate stations were collected from the National Meteorological Information Center of China. The quality and homogeneity of the climatic records from these stations were checked and controlled using the RclimDex software package (http://etccdi.pacificclimate.org/software.shtml). After rejecting 5 stations with inhomogeneous daily precipitation series, 46 stations were finally selected in this study. The locations of the 46 stations are plotted in Fig. 1, and Table 1 lists the emplacement and a brief description of all used stations.

3 Method

Days with precipitation ≥1 mm are considered as rainy days in this study. This threshold excludes very light

Fig. 1 Meteorological stations used in this study and location of Inner Mongolia Autonomous Region, China
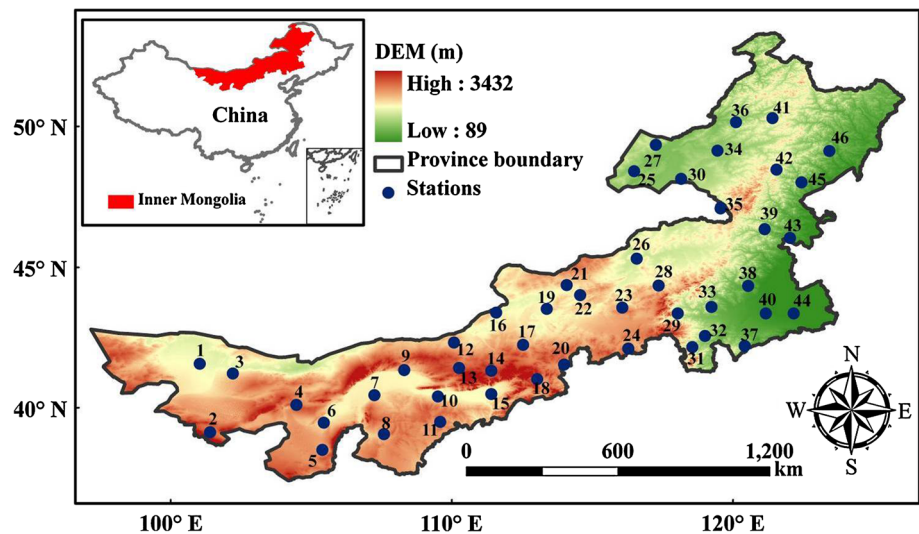
Table 1 List and a brief description of meteorological stations used in this study

No.	Station name	Latitude (N)	Longitude (E)	No.	Station name	Latitude (N)	Longitude (E)
1	Ejin Banner	41.57°	101.04°	24	Duolun	42.11°	116.28°
2	Alxa Right Banner	39.13°	101.41°	25	Xin Barag right Banner	48.4°	116.49°
3	Guaizi Lake	41.22°	102.22°	26	East Ujimqin Banner	45.31°	116.58°
4	Bayan Mod	40.1°	104.48°	27	Manzhouli	49.34°	117.26°
5	Alxa Left Banner	38.5°	105.4°	28	West Ujimqin Banner	44.35°	117.36°
6	Ji Lantai	39.47°	105.45°	29	Linxi	43.36°	118.04°
7	Kanawha	40.45°	107.25°	30	Xin Barag left Banner	48.13°	118.16°
8	Otog Banner	39.06°	107.59°	31	Chifeng	42.16°	118.56°
9	Urat banner	41.34°	108.31°	32	Ongniud Bannar	42.56°	119.01°
10	Baotou	40.4°	109.51°	33	Bairin Left Banner	43.59°	119.24°
11	Dongsheng	39.5°	109.59°	34	Halar	49.13°	119.45°
12	Mandula	42.32°	110.08°	35	Arxan	47.1°	119.56°
13	Darhan Banner	41.42°	110.26°	36	Ergun Right Banner	50.15°	120.11°
14	Siziwang Banner	41.32°	111.41°	37	Bao Guotu	42.2°	120.42°
15	Hohehot	40.49°	111.41°	38	Jarud Banner	44.34°	120.54°
16	Erlianhot	43.39°	111.58°	39	Suolun	46.36°	121.13°
17	Zhu Rihe	42.24°	112.54°	40	Kailu	43.36°	121.17°
18	Jiling	41.02°	113.04°	41	Tulihe	50.29°	121.41°
19	Sonid Left Banner	43.52°	113.38°	42	Bugt	48.46°	121.55°
20	Huade	41.54°	114°	43	Ulanhot	46.05°	122.03°
21	Naran bulag	44.37°	114.09°	44	Tongliao	43.36°	122.16°
22	Abag Banner	44.01°	114.57°	45	Zhalantun	48°	122.44°
23	XilinHot	43.57°	116.07°	46	Xiaoergou	49.12°	123.43°

precipitation and partially accounts for the limited accuracy of rain gauges (Tank and Können 2003). Because of the high random observational errors for very light precipitation, the use of time series including very light precipitation challenges the robustness of the results. Altogether, 15

precipitation indices were used in this study. Detailed information of these indices and related definitions and units are given in Table 2. The Expert Team on Climate Change Detection and Indices (ETCCDI) have defined a lot of extreme indices derived from daily precipitation (http://

Table 2 Definitions of precipitation indices used in this study

Classes	Precipitation indices	Definitions	Unit
Normal precipitation indices	ATP/STP	Annual/seasonal total precipitation	mm
	ATD/STD	Annual/seasonal total number of rainy days	days
	API/SPI	Annual/seasonal precipitation intensity (mean precipitation amount on a rainy day)	mm/day
	AMP/SMP	Annual/seasonal maximum daily precipitation amount	mm
Extreme precipitation indices	NLP	Annual total number of large precipitation days (annual count of days when daily precipitation $\geq$10 mm)	days
	NHP	Annual total number of heavy precipitation days (annual count of days when daily precipitation $\geq$20 mm)	days
	CWD	Annual maximum length of wet spell (maximum number of consecutive rainy days)	days
	MP5	Annual maximum consecutive 5-day precipitation	mm
	TP90	Annual total precipitation amount of rainy days with precipitation exceeding 90th percentile	mm
	TP95	Annual total precipitation amount of rainy days with precipitation exceeding 95th percentile	mm
Precipitation structure indices	OWS	Occurrence frequency of wet spells with different durations	%
	CWS	Fractional contribution of wet spells with different durations to the annual total precipitation amount	%
	ODP	Occurrence frequency of daily precipitation events with different intensities	%
	CDP	Fractional contribution of daily precipitation events with different intensities to the annual total precipitation amount	%
	PCI	A kind of precipitation concentration index represents the degree to which annual total precipitation is distributed over 12 months	

etccdi.pacificclimate.org/software.shtml), and six extreme precipitation indices of these were selected in this study. Besides, the wet spell is a period of consecutive days of exactly, say, *x* wet days immediately preceded and followed by a dry day (Deni and Jemain 2009). The minimum length of a single wet spell is 1 day. Finally, PCI was proposed as an indicator of monthly rainfall heterogeneity (Oliver 1980). It is calculated according to Eq. (1):

$$\mathrm{PCI} = \frac{\sum\limits_{i=1}^{12} P_i^2}{(\sum\limits_{i=1}^{12} P_i)^2} \times 100 \qquad (1)$$

where P_i is the monthly precipitation in month *i*. According to the proposed formulae, the lowest theoretical value of PCI1 is 8.3, indicating the perfect uniformity in precipitation distribution (i.e., that same amount of precipitation occurs in each month). Also, a PCI value of 16.7 will indicate that the annual total precipitation was concentrated in 1/2 of the period and a PCI value of 25 will indicate that the total precipitation occurred in 1/3 of the period (i.e., annual total precipitation occurred in 4 months).

The Mann–Kendall (M–K) trend test suggested by the World Meteorological Organization was used to analyze the trends of these precipitation indices. This test is known as the Kendall's tau statistic, which is a non-parametric test, meaning that it does not assume any priority in the distribution of the data and allows the presence of a tendency over a long period of rainfall data to be observed (Yavuz and Erdoğan 2012). To eliminate the effect of serial correlation on M–K results, the ''pre-whitened'' technique is used to remove the effects of serial correlation before the M–K analysis (Zhang et al. 2001). The 5 % significance level was used as a threshold to classify the significance of positive and negative M–K trends. In M–K test, another very useful index is the Sen's slope, which was also used in this study. Sen's slope is a robust estimate of the magnitude of a trend which has been widely used in identifying the slope of the trend in the hydrological data series (Deni et al. 2010).

To conduct change-point analysis, the non-parametric Mann–Kendall–Sneyers test was employed. The test is a sequential version of the Mann–Kendall rank statistic proposed by Sneyers (1990). In the figure of M–K change-point detection, the UF curve shows the changing trend of a time series. The time series denotes a downward trend if UF < 0 and vice versa, and if the UF value is greater than the critical values, then this upward or downward trend is at >95 % significance level. An intersection point of the UF and UB curves within the confidence interval indicates a change point. A detailed description of the M–K change-point analysis can be found in Liu (2012).

4 Results

4.1 Changes in normal and extreme precipitation indices

To analyze the spatial variations of precipitation, the average values of ATP, ATD, API and AMP series in each station, respectively, are firstly computed. The spatial distributions of the aforementioned four indices are shown in Fig. 2a–d, respectively. From Fig. 2a, ATP depicts a west to east increasing gradient in Inner Mongolia and the value ranges from 38.1 to 483.5 mm. The largest ATP values occur in the northeast area, whereas most of the smallest values locate in the westernmost Inner Mongolia. As described by Fig. 2b–d, ATD, API and AMP show a similar distribution with that of ATP. ATD ranges from 8.0 to 66.4 days, API ranges from 3.7 to 9.1 mm/day and AMP ranges from 10.3 to 58.5 mm. The linear relationships between precipitation indices and latitude and longitude are calculated to reveal the spatial structure of dry spell series, which is shown in Fig. 3. It is very interesting that the relationship between ATP, ATD, API, AMP and latitude are all positive. Similarly, the four precipitation indices increase as longitude increases. Observing the results of determination coefficient R^2, the linear relationships between the precipitation indices and longitude are more significant than those of latitude. It is suggested that the precipitation indices possess the longitude zonality. The reasons mainly lie in two aspects. Firstly, Inner Mongolia

is located in the marginal zone of East Asian monsoon climate and continental climate, mainly controlled by the East Asia monsoon. Secondly, this province is a narrow strip of land sloping from northeast to southwest. It is flanked by the Greater Khingan Mountains on the northeast and Ho-lan Mountains on the west. Yin Mountains run across the central portion of this province. The complex terrain has caused difficulty for the moisture to reach the western area. As a result, west Inner Mongolia is characterized by smaller precipitation amount and fewer rainy days.

Figure 2a–d also illustrates the spatial distribution of trends in ATP, ATD, API and AMP. It can also be seen from Fig. 2a that there are 30 stations characterized by decreasing AP, accounting for 65 % of the total stations. These stations are located mainly in the middle and eastern parts of Inner Mongolia. Similar spatial distribution patterns of the other three precipitation indices (Fig. 2b–d) can be found when compared with those of ATP. Most of the stations in middle and east Inner Mongolia display decreasing trends in ATD, API and AMP, whereas the few stations located in west Inner Mongolia show increasing trends of these precipitation indices. In terms of the number of stations with significant trends, this province is dominated by a weak decreasing tendency of normal precipitation indices. Figure 4a, b shows the abrupt changes in regional precipitation indices detected using the M–K test. Obviously, all the four precipitation indices exhibit a zigzag changing pattern (decreasing–increasing–decreasing)
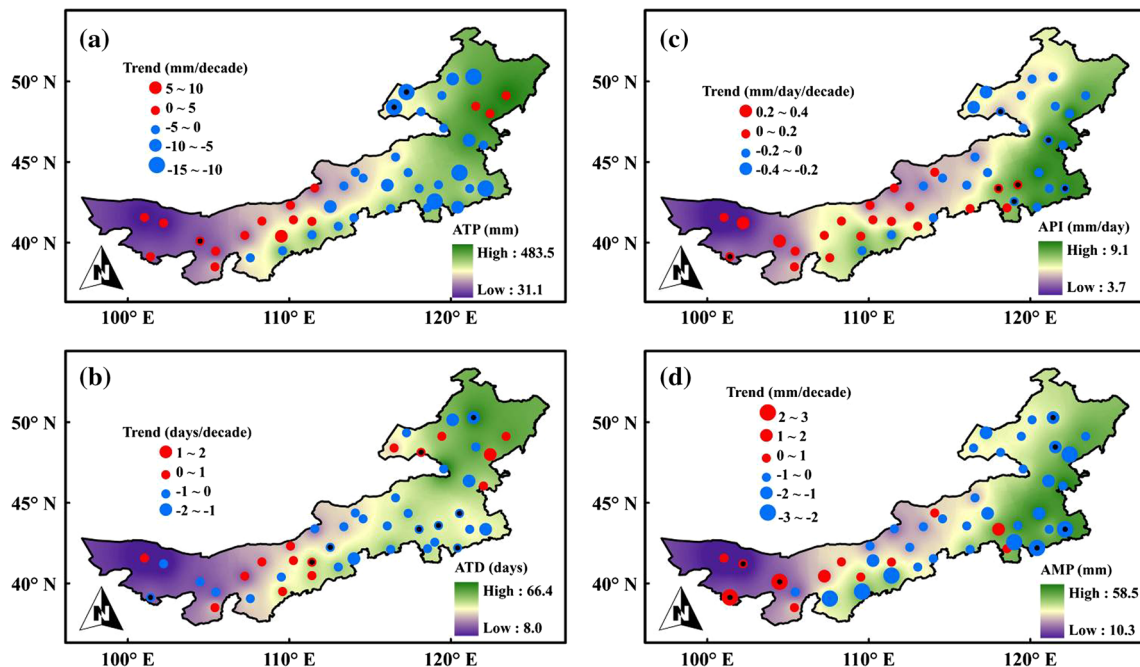
Fig. 2 Spatial distribution for mean values and M–K trends in **a** ATP, **b** ATD, **c** API and **d** AMP across Inner Mongolia (the *color* within Inner Mongolia denotes the mean values of the considered index; the *circles* with *black dots* show significant trends at the 95 % confidence level)
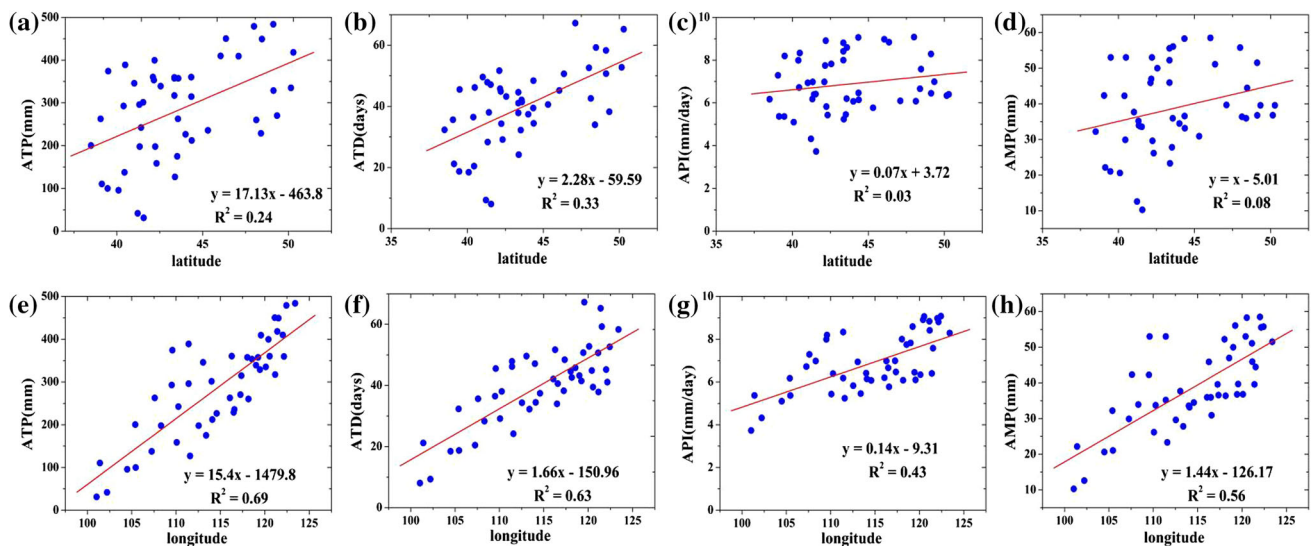
Fig. 3 Relationship between four precipitation indices and latitude and longitude

over Inner Mongolia during 1960–2012. For each index, the jump time mainly occurs during the period of 1975–1980 and 2000–2005, respectively. More specifically, a slight downward trend can be found for all the precipitation indices after 1995. Similarly, Zhang et al. (2011) have found that a decreased moisture flux directly caused more serious and a higher frequency of droughts in northern China after the 1990s. The above-mentioned results indicate decreasing precipitation at the annual time scale, which is reflected by decreasing precipitation amount, rainy days and intensity.

The spatial distribution of long-term mean values of six extreme precipitation indices in this study during 1960–2012 is displayed in Fig. 5. Definitions of these precipitation indices can be found in Table 1. Being similar to the spatial variations of normal precipitation indices (Fig. 2a–d), the extreme precipitation indices also possess the longitude zonality. It is hard to ignore that the average of NHP is 2.6 days with the largest of 6.5 days and the smallest of 0.1 days (Fig. 5b). The largest CWD of 5.9 days and the smallest CWD of 1.7 days is observed in Fig. 5d. These results indicate that the heavy precipitation events and consecutive precipitation events are not prevalent within Inner Mongolia. Figure 5 also demonstrates the spatial distribution of trends in NLP, NHP, CWD, MP5, TP90 and TP95. It can be observed from Fig. 5a that a majority of stations are characterized by increasing NLP and these account for 62.5 % of the total number of stations. However, the increasing trends are statistically significant in only 2 out of 46 stations (Fig. 5a). Differently, for other precipitation indices, stations with decreasing trends are more than those with increasing trends. Among the five indices, TP95 has the largest number of stations showing significant decreasing trends with seven stations at

a significance level of 5 % (Fig. 5f). Regarding other indices, not more than four stations were with significant decreasing trends (Fig. 5b–e). From a spatial perspective, those decreasing trends are mainly observed in middle and east Inner Mongolia. Thus, extreme precipitation events within Inner Mongolia generally show a weak decreasing tendency, which implies the alleviation of the risk of flooding induced by the extreme heavy precipitation to some extent.

4.2 Changes in structure of wet spells

The occurrence frequency of wet spells with different durations (OWS) and fractional contribution of precipitation amount of consecutive precipitation events with different durations to the annual total precipitation amount (CWS) are used to explore the structure of consecutive precipitation events. Figure 6 shows that in Inner Mongolia, the larger the durations of wet spells, the smaller are the OWS and CWS. The precipitation events in Inner Mongolia are mainly subjected to shorter durations of ≤3 days. The OWS with durations of 1–3 days is 96.9 % with CWS being 88.4 %. Wet spells with durations of 1 and 2 days are prevalent in this province. The occurrence frequency of wet spells with duration of 1 day is 70.0 % with the largest CWS being 43.7 %; and that of the consecutive precipitation events with duration of 8 days was 0.04 % only with CWS being 0.23 % only. The structure of wet spell in this study is almost consistent with that in the Yellow River Basin found by Zhang et al. (2014).

Figure 7 illustrates the temporal evolutions of OWS and CWS, respectively. Before analysis, OWS and CWS were standardized and then the 5-year moving average was computed (Zolina et al. 2010). It can be seen from Fig. 7a
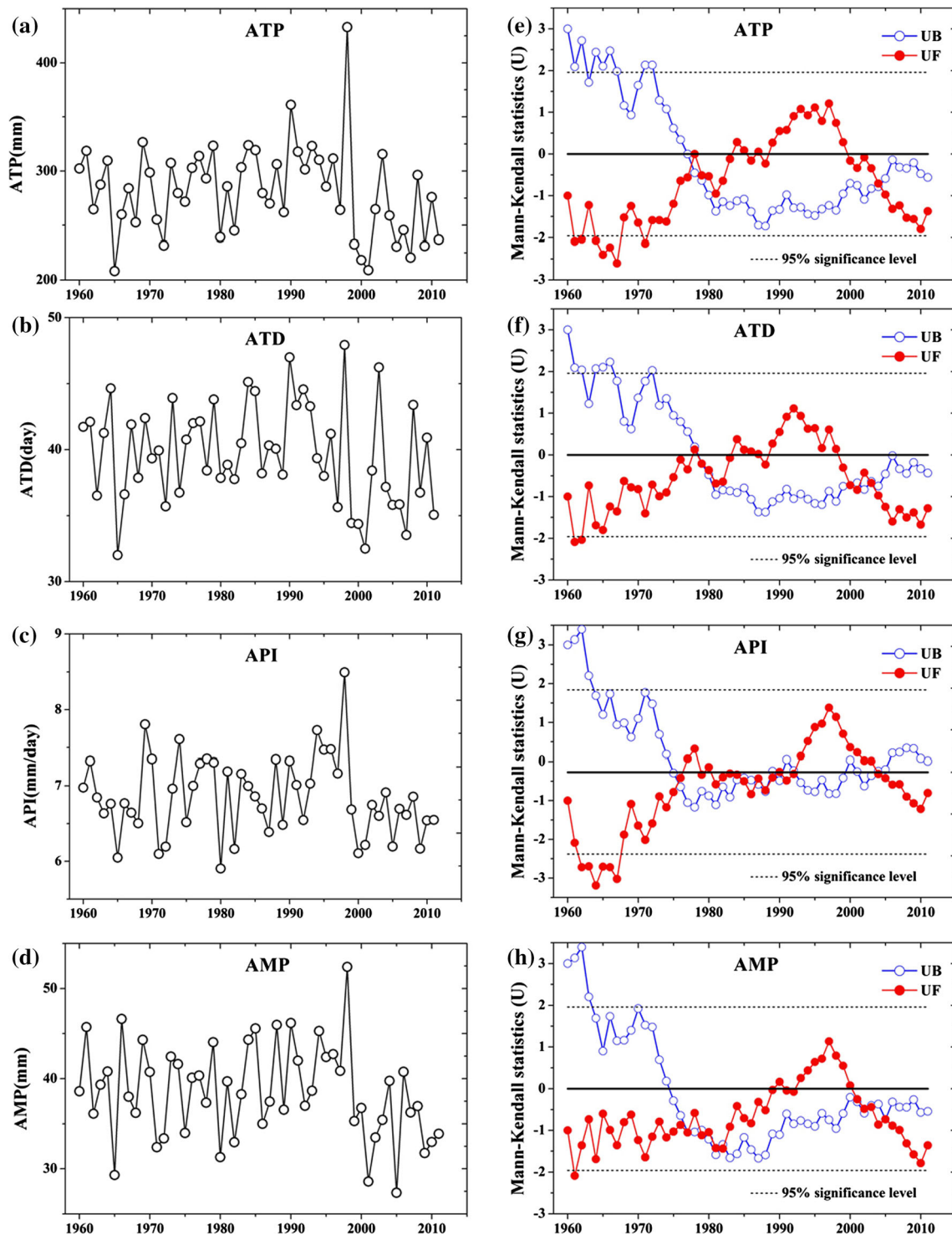
Fig. 4 *Left panel* **a–d** Regional annual series for ATP, ATD, API and AMP. *Right panel* **e–h** Changing points detected using MK method for the four time series. The Mann–Kendall statistics (U) calculated with progressive and retrograde series are named UF (*red line*) and UB (*blue line*), respectively; the *solid line* indicates no trend; the *two dashed lines* mean that upward or downward trend is significant at 5 % significance level

that the patterns of occurrence of wet spells with different durations are slightly ambiguous. However, a relatively evident pattern can still be identified. Before the 2000s,

higher occurrence can be detected for wet spells with moderate durations, e.g., 3–6 days. After the 2000s, however, a higher occurrence is identified for wet spells with
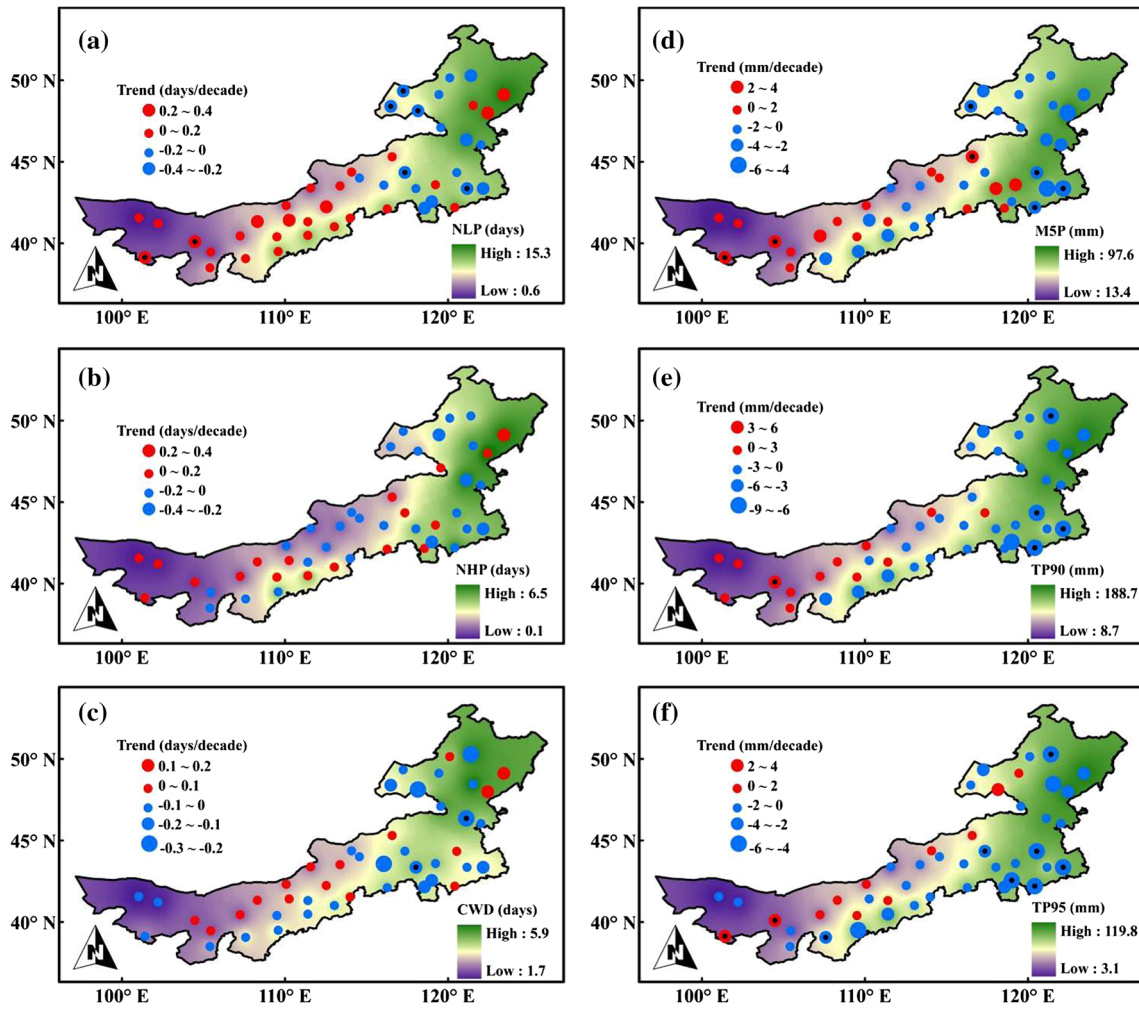
Fig. 5 Spatial distribution for mean values and M–K trends in **a** NLP, **b** NHP, **c** CWD, **d** M5P, **e** TP90 and **f** TP95 across Inner Mongolia (the *color* within Inner Mongolia denotes the mean values of the considered index; the *circles* with *black dots* show significant trends at the 95 % confidence level)
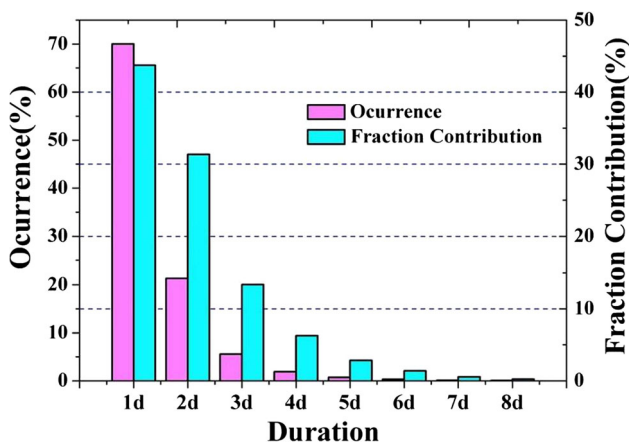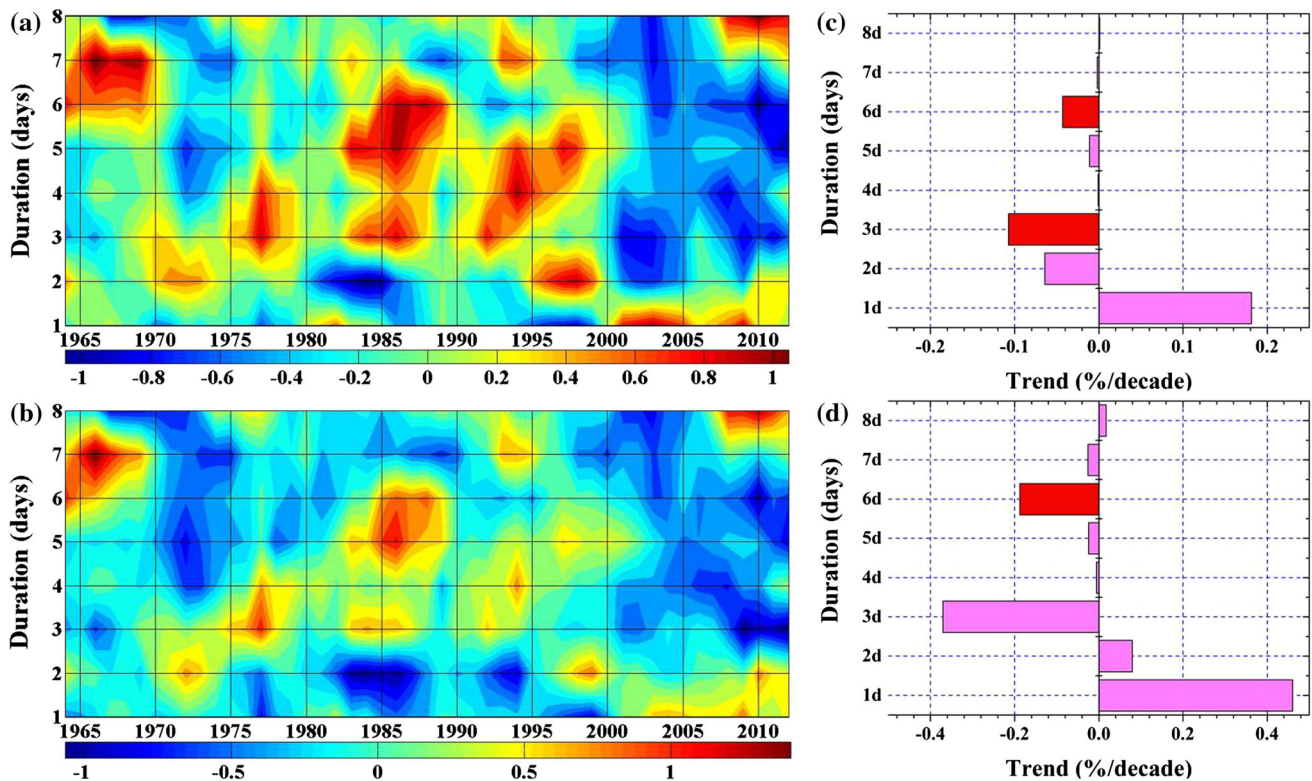

Fig. 6 Occurrences and fractional contributions of wet spells with different durations across Inner Mongolia

durations of 1–2 days. After 1995, a lower occurrence is found mostly for wet spells with durations of larger than 2 days. The temporal evolution of fractional contributions of wet spells presents similar changing properties when compared with that of occurrences (Fig. 7b). As illustrated in Fig. 7c, negative trends can be found in the OWS with durations of 3–7 days, of which the OWS with durations of 3 and 6 days displays significant trends. Similar change trends of CWS (Fig. 7d) can be found when compared with those of OWS. In general, there is decrease in the OWS and CWS with moderate and long durations.
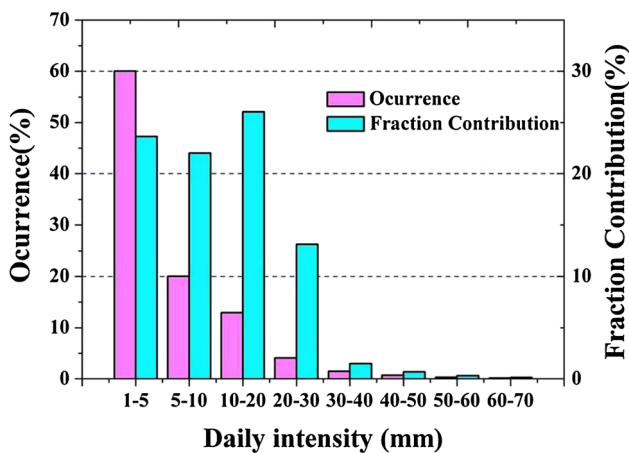
4.3 Changes in structure of daily precipitation events

The occurrence frequency of daily precipitation with different intensities (ODP) and fractional contribution of

Fig. 7 Left panel a–b Temporal evolution in the normalized anomalies of a occurrence and b fractional contributions of wet spells with different durations across Inner Mongolia. Right panel c–d Trends in the c occurrence and d fractional contributions of wet spells with different durations across Inner Mongolia (red bar denotes significant trends detected by Mann–Kendall test at the 95 % confidence level)
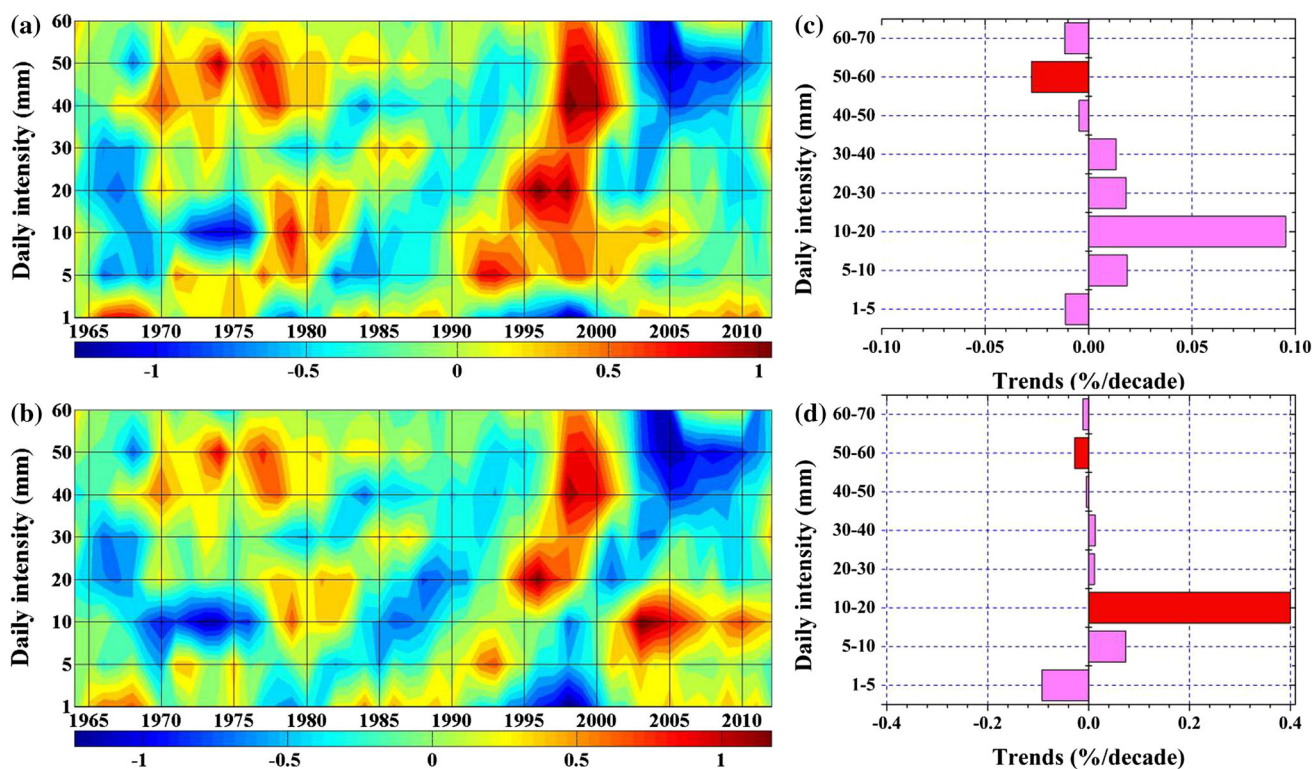

Fig. 8 Occurrences and fractional contributions of daily precipitation events with different intensities across Inner Mongolia

precipitation amount of daily precipitation with different intensities to the annual total precipitation amount (CDP) are used to explore the structure of daily precipitation events. Figure 8 shows that the occurrence of daily precipitation events decreases in an exponential manner with increasing intensity. The occurrence of daily precipitation with intensity of 1–5 mm is the largest, being about

60.1 %, and that of daily precipitation with intensity of more than 60 mm is about 0.14 %. For CDP, changes of fractional contribution and related occurrence frequencies of daily precipitation are not in agreement. The fractional contribution of daily precipitation with intensity of 10–20 mm is the largest, accounting for about 26.0 % of the annual total precipitation amount. The occurrence of daily precipitation with intensity of 1–20 mm is 93.3 % with the fractional contribution being larger than 71.7 %, indicating that light and moderate precipitation events are the major precipitation patterns in Inner Mongolia.

Figure 9 illustrates the temporal evolutions of ODP and CDP, respectively. Before analysis, ODP and CDP were also standardized and then the 5-year moving average was computed (Zolina et al. 2010). It can be seen from Fig. 9a that the patterns of occurrence of daily precipitation with different intensities are slightly ambiguous. However, a relatively evident pattern can still be identified. After the 2000s, lower occurrence can be detected for daily precipitation with high intensity, e.g., 30–70 mm. After the 1990s, however, a higher occurrence is identified for daily precipitation with intensity of 1–20 mm. The temporal evolution of fractional contributions of daily precipitation presents similar changing properties when compared with

Fig. 9 *Left panel* **a–b** Temporal evolution in the normalized anomalies of **a** occurrence and **b** fractional contributions of daily precipitation events with different intensities across Inner Mongolia. *Right panel* **c–d** Trends in the **c** occurrence and **d** fractional contributions of daily precipitation events with different intensities across Inner Mongolia (*red bar* denotes significant trends detected by Mann–Kendall test at the 95 % confidence level)

that of occurrences (Fig. 9b). As illustrated in Fig. 9c, positive trends can be observed in the ODP with intensity of 5–40 mm. Similar change trends of CDP can be found in Fig. 9d; especially, CDP with an intensity of 10–20 mm displays significant trend. Overall, the ODP and CDP with low and high intensity decrease.

4.4 Changes in the seasonal distribution of precipitation

PCI proposed by Oliver (1980) represents the degree to which annual total precipitation is distributed over 12 months. Figure 10a shows the spatial distribution of PCI values, calculated from the monthly precipitation data set of each individual year and averaging over the observation years. These values range from a minimum value of 20.8 to a maximum value of 38.6. It is clearly shown that the higher PCI values are mostly situated in the westernmost Inner Mongolia, and that some areas of middle and east Inner Mongolia are dominated by lower PCI. As described by Oliver (1980), PCI values below 10 indicate a uniform monthly rainfall distribution throughout the year, whereas values from 11 to 20 denote seasonality in rainfall distribution and values above 20

correspond to climates with substantial monthly variability in rainfall amounts (Coscarelli and Caloiero 2012). Obviously, Inner Mongolia is dominated by a substantial monthly variability in intra-annual distribution of precipitation. The temporal distribution of four precipitation indices further explains the higher precipitation concentration across Inner Mongolia (Fig. 11a–d). Precipitation occurs mainly during summer, making up about 70 % of the annual total amount and 60 % of annual total rainy days (Fig. 11a, b). As illustrated in Fig. 11c, d, both the precipitation intensity and maximum daily precipitation in summer are much higher than those of other seasons. Attention should also be paid to the lowest levels of precipitation indices in the winter time scale. Especially, the minimum value of rainy days in winter is less than 2 days, which implies that winter is the driest season with very long dry spells. In wintertime, northern China experiences a strong winter monsoon, which brings cold, dry air from high latitudes and prevents the northward flow of warm, moist air from low latitudes (Sun and Ao 2013). Consequently, there is less water vapor available to form precipitation over northern China, which is one of the main reasons for the lower levels of winter precipitation in Inner Mongolia.
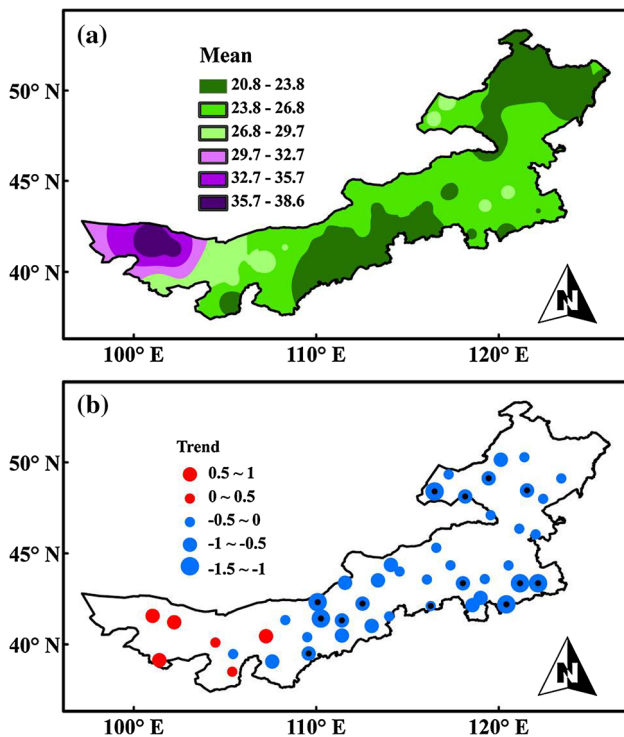
Fig. 10 Spatial distribution for **a** mean values and **b** M–K trends in PCI during 1960–2012 (the *circles* with *black dots* show significant trends at the 95 % confidence level)

The results emerging from the application of Mann–Kendall test to yearly PCI series of each station are shown in Fig. 10b. There are 41 stations characterized by decreasing PCI, accounting for 89 % of the total number of stations. This means that the distribution of the monthly precipitation during the year becomes more uniform in this province. As illustrated in Fig. 10b, 14 stations showing significant decreasing trends are mainly observed in the middle and east Inner Mongolia. The decreasing tendency of PCI across Inner Mongolia is well confirmed by the results obtained by applying the Mann–Kendall test to the seasonal precipitation indices. It can be seen from Fig. 12a, b, d that more stations are characterized by increasing STP, STD and SMP in spring and winter; however, more stations are dominated by decreasing STP, STD and SMP in summer; no distinct difference can be found in the number of stations in autumn. More than half of the stations display positive trends in SPI for each season (Fig. 12c), differing from the changing patterns of STP, STD and SMP. It can also be seen from Fig. 12 that more stations are characterized by significant increasing trends of STP, STD, SPI and SMP in spring and winter, wherein the number of stations with significant changes in STP is the largest in winter, i.e., there are 15 stations, accounting for 32.7 % of the total number of stations, dominated by significantly increasing STP. In contrast, there are 20 stations,

accounting for 43.5 % of the total number of stations, characterized by significant decreasing STD in summer. In addition, abrupt changes in the time series of summer rainy days mostly occurred around 1980 and 2000, respectively (Table 3). As shown in Table 3, most of the time series display downward trends after the end of 1990s. Similar abrupt changes were found in the precipitation indices at the annual scale (Fig. 4).

5 Discussion

Changing characteristics of precipitation were firstly assessed through different precipitation indices at the annual scale, and their variability was analyzed applying the M–K test to the index time series. As illustrated in Figs. 2 and 5, it is worth mentioning that the climate characteristics of "middle-east drying and west wetting" are found across Inner Mongolia. Different climatic systems of middle-east Inner Mongolia and west Inner Mongolia may be considered as the important reason for the different changing patterns of precipitation in the two sub-regions. On the one hand, middle-east Inner Mongolia experiences a semi-humid and semi-arid climate, and is mainly influenced by Eastern Asia monsoon. Since the 1970s, the Asian monsoon circulation is thought to have weakened (Wang 2001). This tends to produce less moisture transport to regions further north. Consequently, the precipitation indices display decreasing trends in middle and east Inner Mongolia. On the other hand, west Inner Mongolia is mainly located at the edge of the monsoon region of China and is mainly controlled by the westerlies. The westerly flow and its moisture transport increased after 1980s in northwest China (Wang et al. 2006; Qian and Qin 2008). This is consistent with the increasing trends of annual precipitation indices in west Inner Mongolia. Thus, for an efficient water resources management under the background of global change and in planning measures for mitigating the adverse impacts of future drought occurrences, the two sub-regions should be separately considered.

Except for the annual scale, seasonal changes of precipitation indices were also explored in this province. As illustrated in Fig. 2, there is a significant change in the seasonal distribution of precipitation in Inner Mongolia, especially in the summer. During the summer period, the total precipitation, rainy days and daily maximum precipitation in most of the stations display decreasing trends, which indicate that this province is dominated by a tendency toward dryness in summer. Warmer waters in the Western Pacific and South China Sea tend to enhance the subtropical high that stalls the summer rain belt for long periods over southern China (Xu et al. 2006). Increasing geopotential height over Mongolia and northern China, the
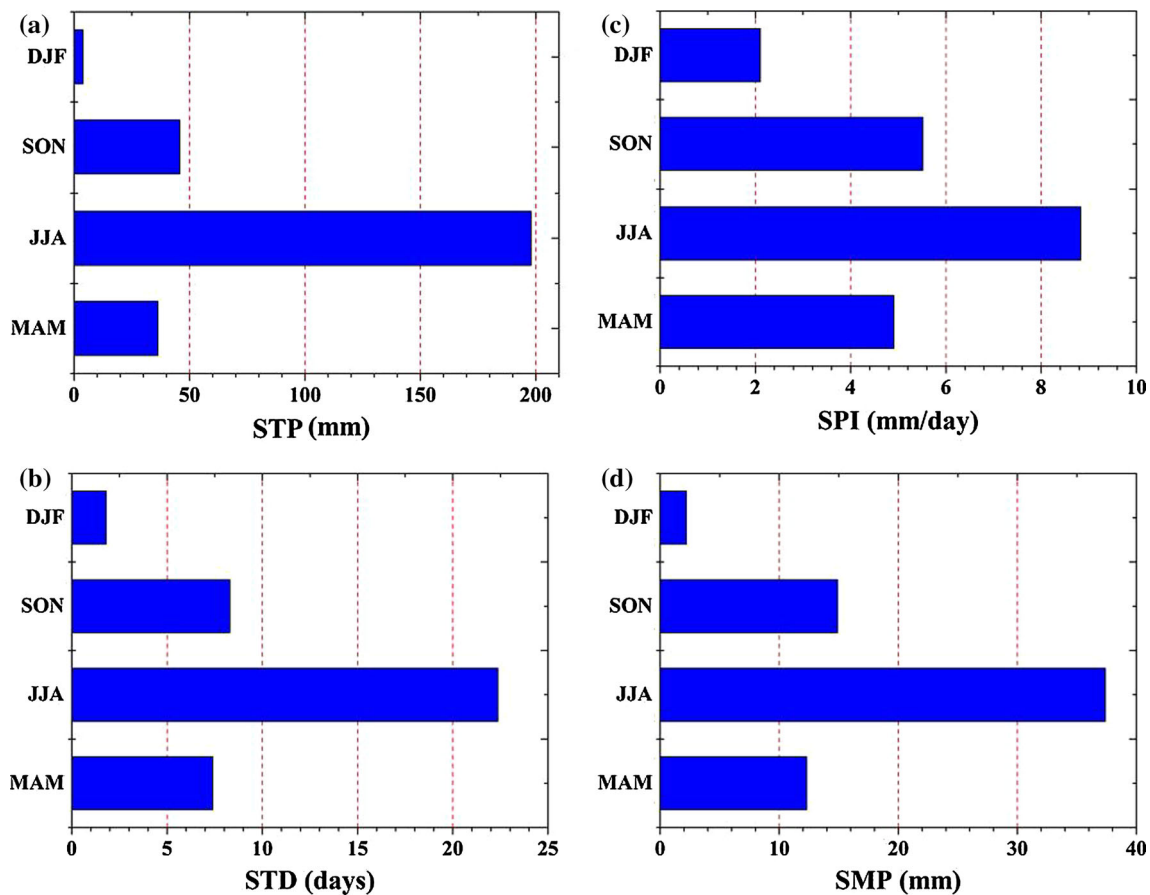
Fig. 11 The intra-annual distribution of **a** STP, **b** STD, **c** SPI and **d** SMP across Inner Mongolia

South China Sea and west Pacific regions has also prevented the northward propagation of the vapor flux, decreasing summer precipitation in northern China (Wang and Zhou 2005). All these changes together with the decline of the Asian monsoonal circulation strength have contributed to the summer drought in Inner Mongolia. In Inner Mongolia, precipitation of summer is the primary climatic factor causing fluctuations in vegetation biomass and coverage (Bai et al. 2008). Both the forest and grassland area of Inner Mongolia rank first in China and play a key role in the ecological shelter of northern China. However, the dry tendency detected in summer may bring in a great negative impact on regional ecological development. In this case, the agriculture forestry and animal husbandry activities in Inner Mongolia should be well organized based on the new phenomenon in the changing climate.

6 Conclusions

There are 15 precipitation indices defined to describe the changing space and time characteristics of precipitation in

Inner Mongolia, providing clues of regional responses of wetness in arid and semi-arid regions of China to global climate changes. The following conclusions are drawn from this study:

(1) A decrease in the precipitation of Inner Mongolia is evident, particularly in the middle and eastern areas, which is reflected mainly by decreasing tendencies of precipitation amount, rainy days and precipitation intensity. In the majority of cases, the most extreme precipitation indices suggest that there is decrease in both the days and the intensity of precipitation extremes. In this case, the risk of floods caused by extreme precipitation events may be alleviated.

(2) Short-duration consecutive precipitation events are prevalent in Inner Mongolia. Trend analysis indicates that the OWS and CWS with short durations, mainly 1–2 days, show an increase, implying that more and more short-duration wet spells occur and contribute more and more to the annual precipitation.

(3) Light and moderate precipitation is the major daily precipitation event in this province. Trend analysis indicates that the ODP and CDP with moderate
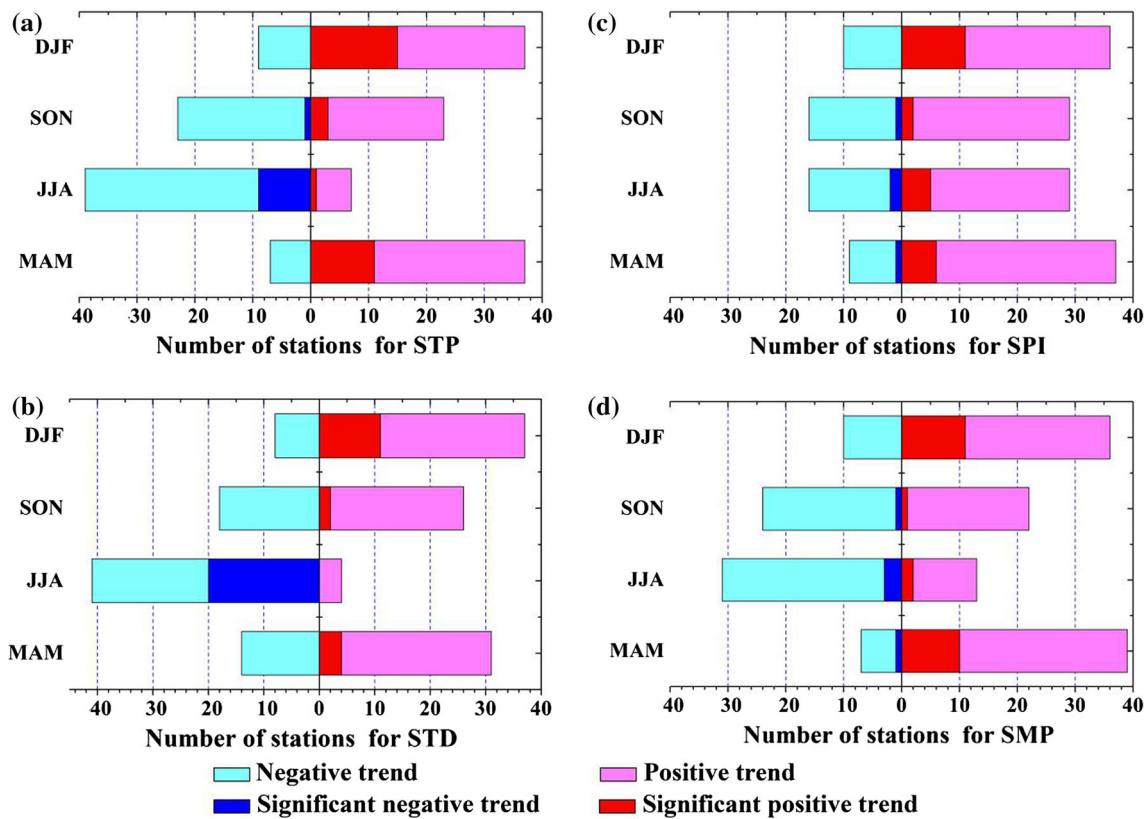
Fig. 12 Number of stations with different M–K trends for **a** STP, **b** STD, **c** SPI and **d** SMP in Inner Mongolia

Table 3 Summary of change points of STD series detected by M–K test during summer in Inner Mongolia

Station No.	Change points	Trend before and after change points	Station No.	Change points	Trend before and after change points	Station No.	Change points	Trend before and after change points
1	×	×	17	1984/2000	↓↓↓	33	1982/2000	↓↓↓
2	1983	↑↓	18	1983/2000	↓↓↓	34	1983/2001	↓↑↓
3	1982	↓↓	19	1982/2002	↓↓↓	35	1983/2000	↓↑↓
4	1983/1998	↑↓↓	20	1976/2005	↓↑↓	36	1983/2000	↓↑↓
5	1977/2003	↓↑↓	21	1983/2001	↓↓↓	37	×	×
6	1977/2002	↓↑↓	22	1978/2004	↓↑↓	38	1984/1999	↓↓↓
7	1982/1996	↓↓↓	23	1976/2004	↓↑↓	39	1987	↓↓
8	1983/1997	↓↑↓	24	1978/2000	↓↓↓	40	1985/1998	↓↓↓
9	1982/1996	↓↓↓	25	×	×	41	1980/2003	↓↑↓
10	1981/1999	↓↑↓	26	1982/2000	↓↑↓	42	1983/2000	↓↓↓
11	×	×	27	1983/2002	↓↑↓	43	1983/2001	↓↑↓
12	×	×	28	1980/1998	↓↓↓	44	1985/1998	↓↓↓
13	1983/2000	↓↓↓	29	1987/1997	↓↓↓	45	1990	↓↓
14	1976/2002	↓↑↓	30	1989	↓↓	46	1964	↓↓
15	1978/2006	↓↑↓	31	1979	↓↓			
16	1981/2000	↓↓↓	32	1983/1999	↓↓↓			

"↑" and "↓" denote increasing trend and decreasing trend, respectively

intensity, mainly 5–40 mm, show an increase, implying that more and more moderate precipitation events occur and contribute more and more to the annual precipitation.

(4) The monthly precipitation heterogeneity in Inner Mongolia is characterized by higher concentration, and precipitation events occur mainly during summer. On the one hand, the tendency toward a more uniform distribution of the monthly precipitation during the year is well confirmed by the results obtained by applying the M–K test to the PCI series. On the other hand, this province is dominated by a dry tendency in summer. Thus, great importance should be attached to the seasonal changes of precipitation.

References

Alexander LV, Zhang X, Peterson TC et al (2006) Global observed changes in daily climate extremes of temperature and precipitation. J Geophys Res 111:D05109. doi:10.1029/2005JD006290

Bai Y, Wu J, Xing Q et al (2008) Primary production and rain use efficiency across a precipitation gradient on the Mongolia plateau. Ecology 89(8):2140–2153

Bao Y, Li XB, Huang LM, Zhang YX, Wang H (2011) Spatial–temporal distribution characteristics of precipitation in Inner Mongolia from 1961-2007. Arid Land Geogr 34(1):52–61 (in Chinese)

Bewket W, Conway D (2007) A note on the temporal and spatial variability of rainfall in the drought-prone Amhara region of Ethiopia. Int J Climatol 27(11):1467–1477

Cannarozzo M, Noto LV, Viola F (2006) Spatial distribution of rainfall trends in Sicily (1921–2000). Phys Chem Earth 31:1201–1211

Coscarelli R, Caloiero T (2012) Analysis of daily and monthly rainfall concentration in Southern Italy (Calabria region). J Hydrol 416:145–150

De Luis M, González-Hidalgo JC, Brunetti M, Longares LA (2011) Precipitation concentration changes in Spain 1946-2005. Nat Hazards Earth Syst Sci 11(5):1259–1265

Deni SM, Jemain AA (2009) Fitting the distribution of dry and wet spells with alternative probability models. Meteorol Atmos Phys 104(1–2):13–27

Deni SM, Suhaila J, Zin WZW, Jemain AA (2010) Spatial trends of dry spells over Peninsular Malaysia during monsoon seasons. Theoret Appl Climatol 99(3–4):357–371

Gao T, Xiao SJ, Wu L (2009) Temporal–spatial characteristics of precipitation and temperature in Inner Mongolia for the last 47 years (1961–2007). Inn Mong Meteorol 1:3–7 (in Chinese)

Gong DY, Wang JA, Han H (2005) Trends of summer dry spells in China during the late twentieth century. Meteorol Atmos Phys 88(3–4):203–214

Huang J, Sun SL, Zhang JC (2013) Detection of trends in precipitation during 1960–2008 in Jiangxi province, southeast China. Theor Appl Climatol 14:237–251

Karl TR, Easterling DR (1999) Climate extremes: selected review and future research directions. Clim Change 42(1):309–325

Liang L, Li L, Liu Q (2011) Precipitation variability in northeast China from 1961 to 2008. J Hydrol 404(1):67–76

Liu L (2012) Xu ZX, Huang JX (2012) Spatio-temporal variation and abrupt changes for major climate variables in the Taihu Basin, China. Stoch Environ Res Risk Assess 26:777–791

Oliver JE (1980) Monthly precipitation distribution: a comparative index. Geographer 32:300–309

Pei H, Hao l, Han JW (2011) Pentad precipitation changes during recent 40 years in Inner Mongolia. J Appl Meteorol Sci 23(5):543–570 (in Chinese)

Qian WH, Qin A (2008) Precipitation division and climate shift in China from 1960 to 2000. Theoret Appl Climatol 93(1–2):1–17

Santo FE, Ramos AM, de Lima MIP, Trigo RM (2013) Seasonal changes in daily precipitation extremes in mainland Portugal from 1941 to 2007. Reg Environ Change 1–24

Shi P, Qiao X, Chen X, Zhou M, Qu S, Ma X, Zhang Z (2014) Spatial distribution and temporal trends in daily and monthly precipitation concentration indices in the upper reaches of the Huai River, China. Stoch Env Res Risk Assess 28(2):201–212

Sneyers R (1990) On statistical analysis of series of observations. WMO Tech Note, WMO: 14

Sun J, Ao J (2013) Changes in precipitation and extreme precipitation in a warming environment in China. Chin Sci Bull 58(12):1395–1401

Tank AMG, Können GP (2003) Trends in indices of daily temperature and precipitation extremes in Europe, 1946–99. J Clim 16(22):3665–3680

Wang HJ (2001) The weakening of the Asian monsoon circulation after the end of 1970′s. Adv Atmos Sci 18:376–386

Wang YQ, Zhou L (2005) Observed trends in extreme precipitation events in China during 1961–2001 and the associated changes in large-scale circulation. Geophys Res Lett 32:L09707

Wang BJ, Huang YX, Tao JH, Li DL, Wang PX (2006) regional features and variations of water vapor in northwest China. J Glaciol Geocryol 28(1):15–21 (in Chinese)

Wang W, Shao Q, Peng S, Zhang Z, Xing W, An G, Yong B (2011) Spatial and temporal characteristics of changes in precipitation during 1957–2007 in the Haihe River basin, China. Stoch Environ Res Risk Assess 25(7):881–895

Wang W, Shao Q, Yang T, Peng S, Yu Z, Taylor J, Xing W, Zhao C, Sun F (2013) Changes in daily temperature and precipitation extremes in the Yellow River basin, China. Stoch Environ Res Risk Assess 27:401–421

Xu M et al (2006) Steady decline of east Asian monsoon winds, 1969–2000: evidence from direct ground measurements of wind speed. J Geophys Res Atmos 111:D24111

Yavuz H, Erdoğan S (2012) Spatial analysis of monthly and annual precipitation trends in Turkey. Water Resour Manage 26(3):609–621

Zhang X, Harvey DK, Hogg WD, Yuzyk TR (2001) Trends in Canadian streamflow. Water Resour Res 37(4):987–998

Zhang ZX, Zhang Q, Chen X, Zhang JC, Zhou JW (2011) Statistical properties of moisture transport in East Asia and their impacts on wetness/dryness variations in North China. Theor Appl Climatol 104(3):337–347

Zhang Q, Singh VP, Peng JT, Chen YD, Li JF (2012) Spatial–temporal changes of precipitation structure across the Pearl River basin, China. J Hydrol 440–441:113–122

Zhang Q, Peng J, Singh VP, Li J, Chen YD (2014) Spatio-temporal variations of precipitation in arid and semiarid regions of China: the Yellow River basin as a case study. Glob Planet Change 114:38–49

Zolina O, Simmer C, Gulev SK, Kollet S (2010) Changing structure of European precipitation: Longer wet periods leading to more abundant rainfalls. Geophys Res Lett 37(6)