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Regional trends in recent precipitation indices in China

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With 13 Figures

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Summary

Regional characteristics of recent precipitation indices in China were analyzed from a daily rainfall dataset based on 494 stations during 1961 to 2000. Some indices such as precipitation percentiles, precipitation intensity, and precipitation persistence were used and their inter-decadal differences were shown in this study.

Over the last 40 years, precipitation indices in China showed increasing and decreasing trends separated into three main regions. A decreasing trend of annual precipitation and summer precipitation was observed from the southern part of northeast China to the mid-low Yellow River valley and the upper Yangtze River valley. This region also showed a decreasing trend in precipitation intensity and a decreasing trend in the frequency of persistent wet days. On the other hand, increasing trends in precipitation intensity were found in the Xinjiang region (northwest China), the northern part of northeast China, and southeast China, mainly to the south of the mid-low Yangtze River. The indices of persistent wet days and strong rainfall have contributed to the increasing frequency of floods in southeast China and the Xinjiang region in the last two decades. Persistent dry days and weakening rainfall have resulted in the increasing frequency of drought along the Yellow River valley including North China.

Regional precipitation characteristics and trends in precipitation indices indicate the climate state variations in the last four decades. A warm-wet climate state was found in northwest China and in the northern part of northeast China. A warm-dry climate state extends from the southern part of northeast China to the Yellow River valley, while a cool-wet summer was found in southeast China, particularly in the mid-low Yangtze River valley over the last two decades.

1. Introduction

Extreme weather events can cause large losses of life and tremendous economic losses. The most severe damages seem to concern precipitation on a regional scale. Human fatalities and property losses have helped raise the alarm over the possibility that the recent increases in climate extremes are due to a shifting climate (Easterling et al, 2000). Increasing drought frequency and its persistence might be one of the consequences of global warming. Walsh and Pittock (1998) suggest that the potential changes in tropical storms, hurricanes, and extreme rainfall events are a result of climate change. In China, daily precipitation data sets spanning the last 50 years are available and different climate consequences have been reported in various areas. In northern China, changes in extreme temperature and precipitation during the second half of the 20th century were investigated (Zhai and Pan, 2003; Gong and Han, 2004) while in southern China, frequent floods were also experienced over the last two decades (Zhai et al, 1999; Gong and Ho, 2002). Recently, Shi et al (2003) have indicated that the regional climate in northwest China exhibited a climate state transition from a warm-dry state to a warm-wet state over the last two decades. It was noted that the persistence of drought and flood in a country or a continent is not universal from place to place.

Large data sets of high-quality daily precipitation series on wide spatial and temporal scales are critical in detecting extreme rainfall events (Houghton et al, 1996; Brunetti et al, 2002). China is strongly influenced by the East Asian monsoon. During the summer period, the rain belt moves gradually from south to north with the hot and humid climate in eastern China (Qian et al, 2002). Precipitation variability is one of the major features in China. In some years, rainfall amounts are abundant enough to cause floods, while in other years there is too little rain to support agriculture (Qian et al, 2003). Climate extremes are extensive in China, on wide spatial-temporal scales, and have a significant contribution to climate change.

In order to identify the trends in climate extremes in China, the daily precipitation and daily temperature based on about 494 stations during 1961–2000 are used in this paper. Quality control and the analysis method are described in the next section. Climatic precipitation features including mean state and maximum–minimum difference in China are illustrated in Sect. 3. Regional trends of precipitation indices based on various categories are shown in Sects. 4–6. Conclusions and discussion are given in Sect. 7.

2. Quality control and method

2.1 Quality control

Climate data are essential to our effort to identify and understand variations and changes in regional and global climate. Recently, a global daily meteorological dataset was developed at the U.S. National Climatic Data Centre (NCDC) (Gleason, 2002). This global daily meteorological data-set contains surface air temperature and precipitation from 1951 to the 1990s at 196 stations in China (Gleason, 2002). In fact, this maximum number of 196 stations was only in operation during 1950s. Many studies have used data from the 160 stations in operation since 1951. After 1960 however, the station network became much denser.

Daily data from 726 stations were obtained from the Chinese National Meteorological Center. These data are observations of 10 variables, including daily maximum surface air temperature, daily minimum surface air temperature, daily mean surface air temperature (*Td*), and daily total precipitation (*Pr*). The stations are fairly evenly distributed in the plains east of 95° E longitude. A large void exists in the western Tibetan Plateau and the Tarim Basin in Xinjiang province (the largest desert region in China). Although the number of stations in service has changed over the years, the total number of stations that measure *Pr* and *Td* has remained at about 660 stations after the network was established around 1958. In the early 1950s, the number of observational stations ranged from about 160 to 400.

The method of quality control (QC) is based on the daily values of temperature and precipitation from individual stations with established extreme values. A detailed description of the QC method can be found in the recent work of Feng et al (2004) and Qian and Lin (2004). The QC includes the internal and spatial consistency between the daily mean, maximum and minimum temperatures. To minimize the influences associated with temporal inhomogeneity, stations with serious relocation events, and data records with erroneous types and incorrect units, readings, or data coding, are removed. The sources causing the spatial inconsistencies/discontinuities, as well as those stations with unusual altitudes (higher-mountain stations) compared to the neighboring stations were removed.

After the procedures mentioned above, some possible sources, which may cause error, were eliminated and some scattered missing data were filled in. For the daily precipitation series, the stations with long consecutive missing data (>8 d) or too much missing data in total (>30 d) were omitted.

Considering the QC of temperature, 56 large-city stations were removed (Qian and Lin, 2004). Finally, we obtain high-quality series of daily temperature and daily precipitation for a set of 494 stations (Fig. 1a) from 1961 to 2000, based on the above testing and quality control.

2.2 Method of analysis

Numerous precipitation indices have been used in previous studies of climate extremes. Some indices involve arbitrary thresholds, such as the number of days each year with daily rainfall exceeding 25.4 mm or 50.8 mm (Groisman et al, 1999). As indicated by Monton et al (2001), these are suitable for regions with little spatial

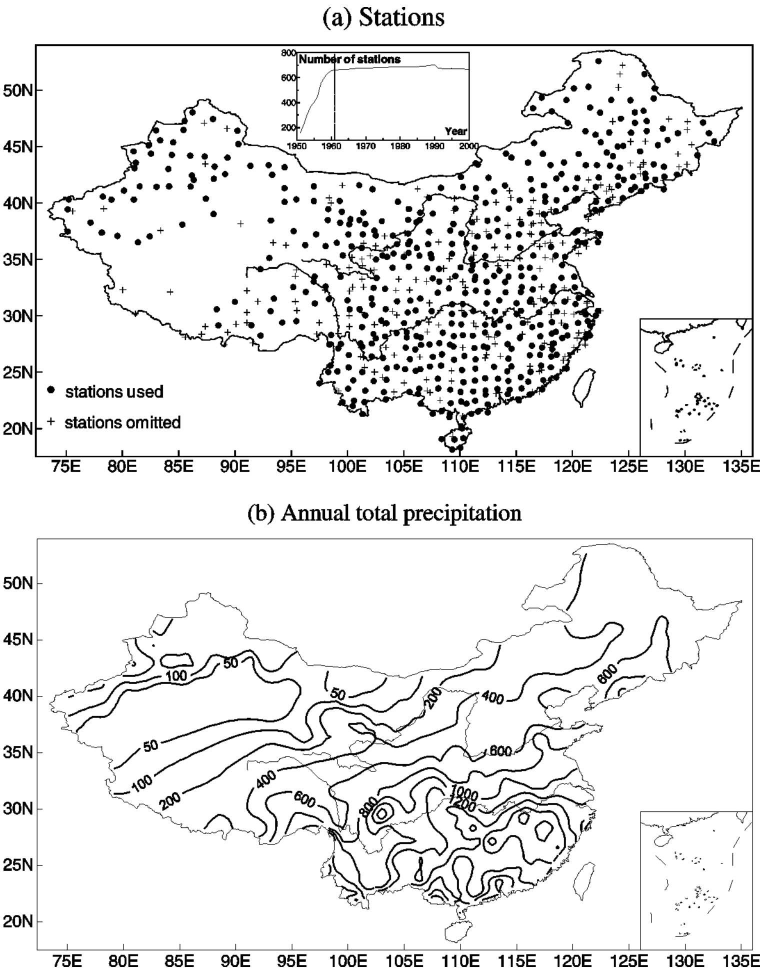

Fig. 1a. Stations for which daily data were available in China, with symbol "●" used in the paper and with symbol " + " omitted due to quality control, and (**b**) annual mean precipitation (mm) for 1961 to 2000. The upper small figure in (**a**) indicates the total number of stations from 1951 to 2000

variability in climate, but arbitrary thresholds are inappropriate for regions spanning a broad range of climates. In China, climates vary widely from the monsoon region in the eastern part to the westerly region in the northwestern part of the country, so there is no single rainfall threshold that would be appropriate for all regions. For this reason, some studies have used extreme indices

Table 1. Precipitation indices

Category	Index	Description
1. Precipitation percentile	R95p	Days with RR > 95th percentile of daily precipitation (very wet days)
	DR95p	Difference of R95p between two 20-year periods (Frich et al, 2002)
	R90N	No. of events > long-term 90th percentile
2. Precipitation intensity	R10 mm	Days with RR $\geq$ 10 mm/d
	DR10 mm	Difference of R10 mm between two 20-year periods
	SDII	Simple daily intensity index (total rainfall/total rain-day per year)
	R3d	Greatest 3-day total rainfall per year
	R5d	Greatest 5-day total rainfall per year
	R10d	Greatest 10-day total rainfall per year
3. Precipitation persistence	CDD	Maximum number of consecutive dry days (RR < 1 mm/day)
	DCDD	Difference of CDD between two 20 yr periods
	CWD	Maximum number of consecutive wet days (RR $\geq$ 1 mm/day)
	DCWD	Difference of CWD between two 20 yr periods
	PWD	Percentage of total persistent wet days (>1 mm) and total rain days
	PDD	Percentage of total persistent dry days and total dry days

based on statistical quantities such as the 10th (5th) or 90th (95th) percentile (Plummer et al, 1999; Peterson et al, 2002). Detailed information can be found from the European Climate Assessment & Dataset (EC&D) Indices List (www.knmi.nl/samenw/eca). Upper and lower percentiles are used in all regions, but vary in absolute magnitude from site to site.

As this study covers a broad region in China, extreme climate indices were based on the 90th and 95th percentiles as well as other precipitation indices, such as the precipitation intensity and precipitation persistence. The precipitation intensity includes, for example, the annual days of daily rainfall larger than 10 mm/d and the greatest 5 d total rainfall per year. The dry persistence and wet persistence are based on the yearly maximum number of consecutive dry days (CDD) with daily rainfall below 1 mm and the yearly maximum number of consecutive wet days (CWD) with the daily rainfall above 1 mm. Fixed thresholds are taken only if these values can be used at any site. A least squares approach for calculating the linear trend and the Kendall_tau significance test (Kendall et al, 1981) are used. The t-test is also used when analyzing the inter-decadal difference, as applied in Frich et al (2002). This paper uses the yearly indices of extremes listed in Table 1. A total of 15 precipitation indices and their trends are shown.

3. Precipitation features

In order to better understand the contribution of extreme indices to mean climate in regional China, the average climatology and interannual maximum–minimum differences of annual precipitation are first described using the updated data series. Figure 1b shows the annual rainfall distribution with larger values from 1600 mm to 1800 mm situated in southeast China and lower

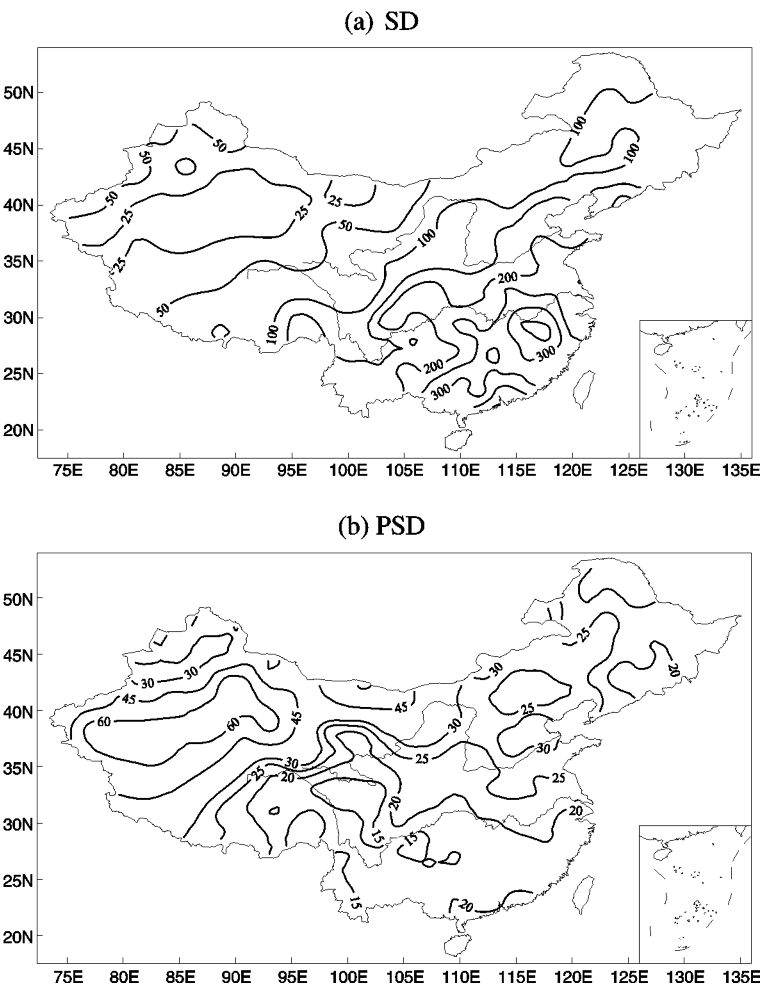

Fig. 2a. The standard deviations (SD, mm) of annual precipitation, and (**b**) their percent SD (PSD, units: %) based on the annual precipitation from 1961 to 2000

values (< 100 mm) in northwest China. In China, many deserts are located in the regions where precipitation is less than 100 mm. Two large gradient zones of precipitation can be observed basically along 200–400 mm and 1000–1400 mm. The former is the last rainfall boundary of the summer monsoon oriented from southwest to northeast, crossing the country, and the latter is the summer rainfall front along the Yangtze River. In northwest China, another region of rainfall, of more than 100 mm, can be found in the northern Xinjiang region.

The standard deviation (SD) of annual precipitation and percent standard deviation (PSD) of annual precipitation are shown in Fig. 2. The PSD is defined as the percent ratio of standard deviation to the annual-mean precipitation. Higher SDs of more than 250 mm can be found in southeast China while lower deviations of less than 50 mm are located in northwest China (Fig. 2a). A long and large gradient zone with SDs of 100–200 mm is observed from the eastern Tibetan Plateau to the northern part of northeast China. The centers of larger SD in southeast China are usually affected by severe flood and drought on the interannual time scale. Differing from SD, PSD (Fig. 2b) indicates the relative variation. Low PSDs of less than 20% exist in the eastern Tibetan Plateau and south of the Yangtze River, where there are large annual-mean precipitations. In northern China, the value of annual-mean precipitation is lower so higher PSDs are found here. The largest PSDs (60%) are found in the largest desert (Tarim Basin) over the southern part of Xinjiang. The PSDs imply that serious drought often affects such places, for example, the upper and lower valleys of the Yellow River where the PSD is above 30%.

The climate mean precipitation and their SDs or PSDs cannot reflect the extreme value of annual precipitation experienced. Figure 3 shows the maximum annual precipitation and minimum

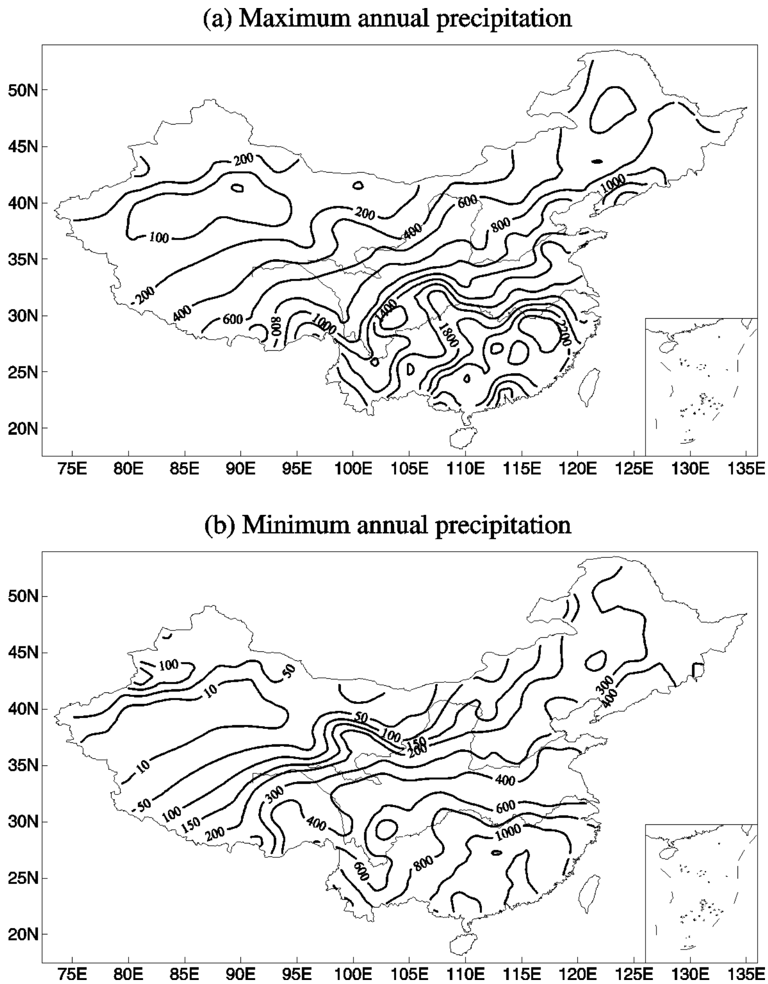

Fig. 3a. Maximum annual precipitation (mm), and (**b**) minimum annual precipitation (mm) based on station observations from 1961 to 2000

annual precipitation based on observations from each station for the period 1961–2000. The distribution pattern of maximum annual precipitation (Fig. 3a) and minimum annual precipitation (Fig. 3b) was similar to those of annual mean precipitation (Fig. 1b). In the last 40 years, the maximum annual precipitation with a value of more than 2200–2600 mm can be found in the stations near the mid Yangtze River and near the south coast. In the lower Yellow River valley, a value of 1000 mm of precipitation has even occurred. The maximum annual precipitation values of 100 mm were recorded in the Tarim Basin. The maximum annual precipitation values

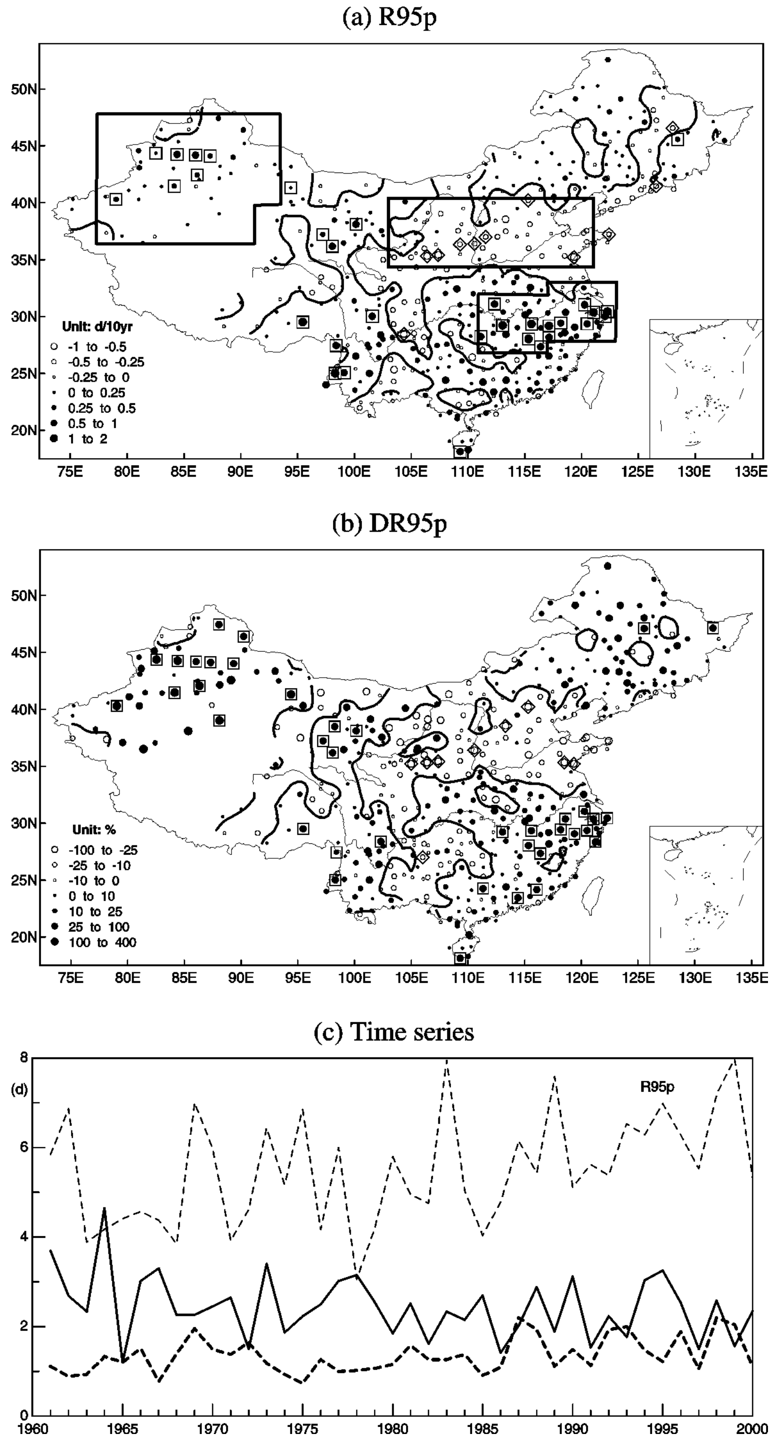

Fig. 4a. Trends (units: d/10 yr) of the days with daily rainfall exceeding the mean-95th percentile for 1961 to 2000 (R95p), (**b**) the ratio (units: %) of the difference of R95p (DR95p) between 1981–2000 and 1961–1980 relative to the first period R95p, and (**c**) the time series of the three boxes in (**a**): the Yellow River valley (solid line), the Xinjiang region (thick dashed line), and the lower Yangtze River valley (thin dashed line). Squares indicate statistical significance at the 0.05 confidence level for the upward trend, and diamonds indicate statistical significance at the 0.05 confidence level for the negative trend in (**a**) and (**b**). The circle size denotes the magnitude of trends and the thick solid line indicates the 0-value contour corresponding to different indices in (**a**) and (**b**)

shown in this figure only indicate the maximum rainfall at a given station or location that has occurred once in the 40-year period.

It is very interesting to compare the minimum annual precipitation to the maximum annual precipitation. The contour of 600 mm precipitation in Fig. 3a is along the upper Yellow River while it lies along the Yangtze River in Fig. 3b. The minimum precipitation to the north of the low Yellow River is below 300 mm. To the south of the Yangtze River, the ratio of minimum annual precipitation to maximum annual precipitation is about 1:2, while the ratio can reach 1:4 along the Yellow River valley. In the desert region over northwest China, the ratio is nearly 1:10. However, maximum annual precipitation of around 100 mm is still not enough to support vegetation due to the huge evaporation in desert regions. In the eastern monsoon region, severe dry events which occur frequently along the Yellow River valley identify this region as a key vulnerable region in China.

4. Precipitation percentile

For extreme precipitation (Fig. 4a), increasing trends (days) where the daily rainfall exceeds the mean 95th percentile for 1961 to 2000, were concentrated near the mid-low Yangtze River valley, Xinjiang, and some stations in southwest China whilst decreasing trends (days) were mainly located along the Yellow River. The ratio of the difference (Fig. 4b) of rainfall-mean 95th percentile (DR95p) between 1981–2000 and 1961–1980 was constructed using the method outlined in Frich et al (2002). During the last two decades, relatively large rainfall amounts increased significantly in part of the Xinjiang region and the lower Yangtze River while it decreased largely along the Yellow River. The absolute values of changes were from between 25%–50% in some regions. Three time series selected from the boxes in Fig. 4a are shown in Fig. 4c. The mean number of R95p in the box of the lower Yangtze River was close to 5 days and the other two curves in the Xinjiang region and the Yellow River were much smaller than 5 days. This means that very wet days increased in the eastern monsoon region and in the low latitudes. A decreasing trend of extreme precipitation was observed from the series along the Yellow River while an increasing trend was noted over the Xinjiang region and the lower Yangtze River (0.42 d/10 yr). An interannual variability of the daily rainfall exceeding the mean-95th percentile was notable in the lower Yangtze River valley, with the maximum difference of about 5 days.

The trends (d/10 yr) of events of daily rainfall larger than the long-term 90th percentile showed significant regional differences (Fig. 5). Three different zones can be seen: (1) from the northern part of northeast China to the Xinjiang region in western China, (2) from the southern part of northeast China to the Yellow River, and part of the upper Yangtze River, and (3) in the region of southeast China. Increasing numbers of precipitation extremes were found in the northern part of Xinjiang, the eastern Tibetan Plateau, and southeast China.

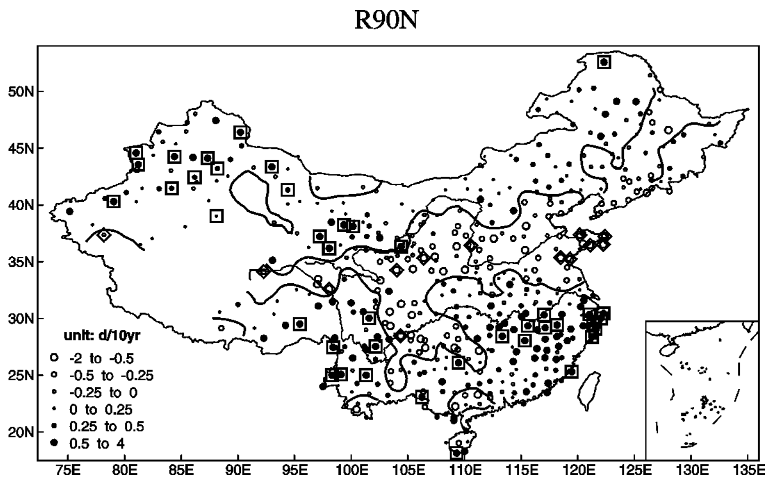

Fig. 5. Trends (units: d/10 yr) of events for daily rainfall larger than the long-term 90th percentile. Symbols and lines as in Fig. 4a

5. Precipitation intensity

The trend distribution (d/10 yr) of the number of days with daily rainfall above 10 mm and the ratio of their difference between 1961–1980 and 1981–2000 are shown in Fig. 6. The strong rainfalls decreased along the Yellow River valley and the

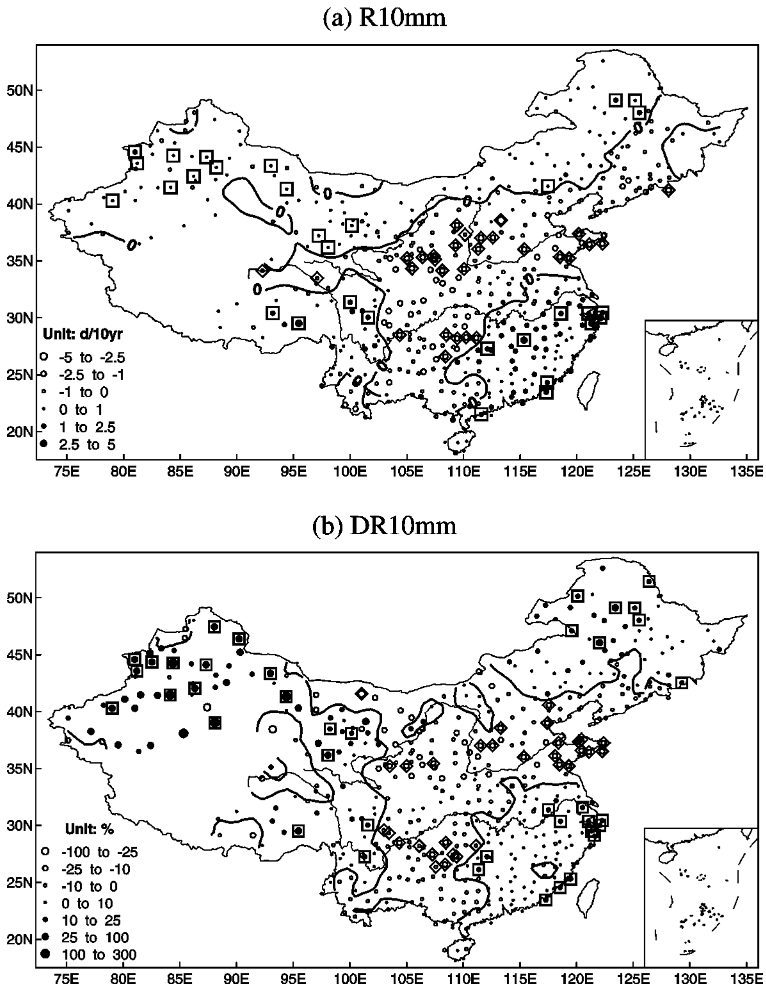

Fig. 6a. Trends (units: d/10 yr) of (**a**) days with the daily rainfall above 10 mm, and (**b**) the ratio (units: %) of their difference between 1961–1980 and 1981–2000 in percentage of interdecadal change to the mean of 1961–1980. Symbols and lines as in Fig. 4a

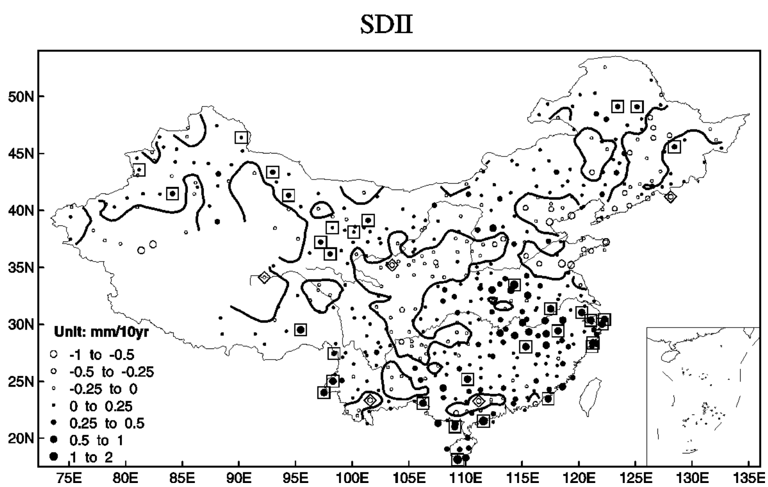

Fig. 7. Trends (units: mm/10 yr) of simple daily intensity index (SDII) based on total daily precipitation and total wet days (> 1 mm/d) per year. Symbols and lines as in Fig. 4a

middle of the Yangtze River valley, while strong rainfalls increased in the Xinjiang region, the northern part of northeast China and southeast China near the coast (Fig. 6a). Changes in the two-decade ratio of rainfall greater than 10 mm, also validate the variation in these regions (Fig. 6b).

The trends (mm/d) of simple daily intensity index (SDII) based on total daily precipitation and total wet days (>1 mm/d) per year are displayed in Fig. 7. The SDII values strengthened mainly in the mid-low Yangtze River, the south coast, and at some sites in northwest and northeast

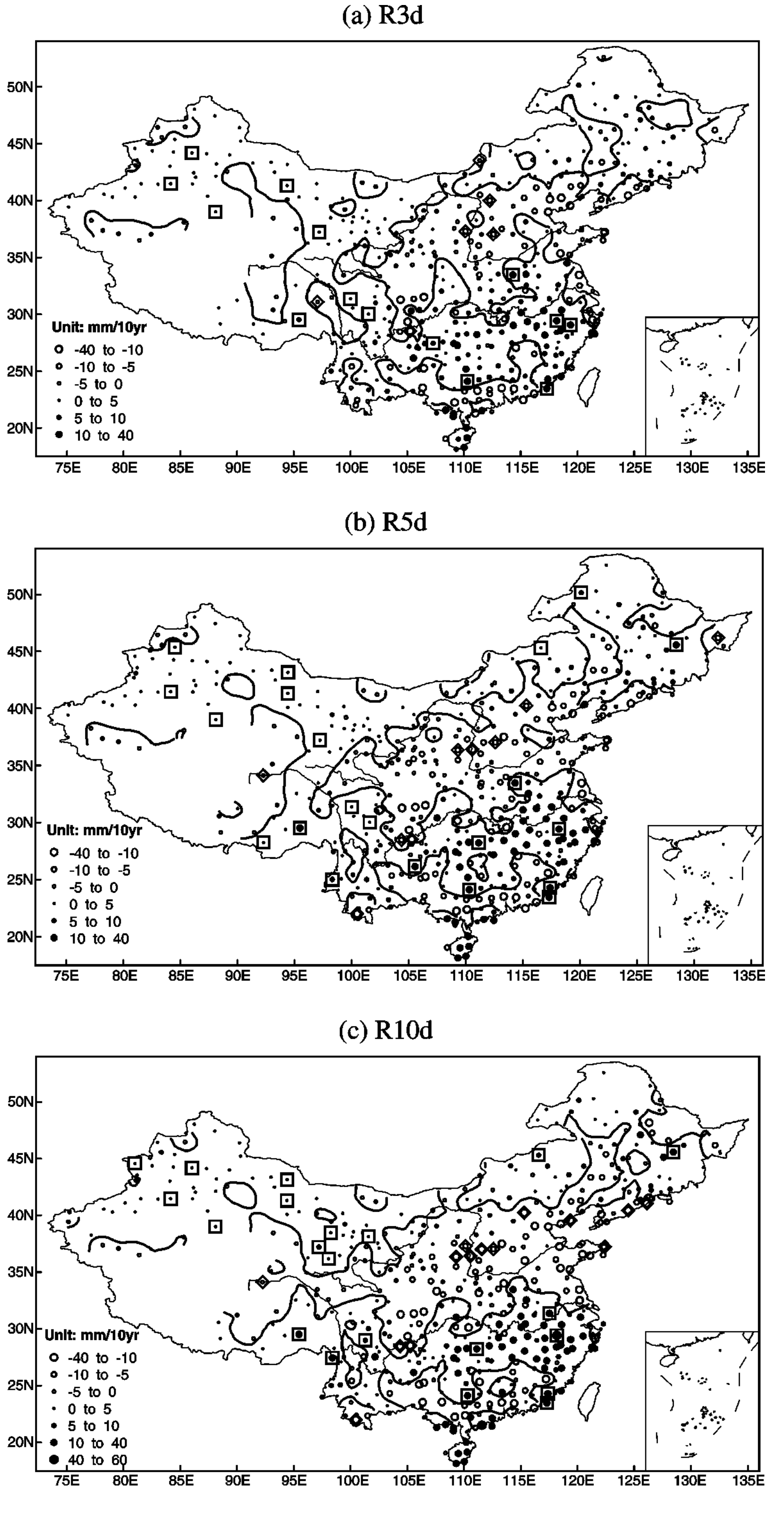

Fig. 8. Trends (units: mm/10 yr) of the greatest (**a**) 3-day, (**b**) 5-day, and (**c**) 10-day rainfalls per year. Symbols and lines as in Fig. 4a

China. Increasing trends of 0.5 mm/10 yr to 1.0 mm/10 yr with a statistical significance of 0.05 can be found in the lower Yangtze River valley and some stations near the south coast.

Trends of the greatest 3 d, 5 d, and 10 d rainfall per year can be found in Fig. 8. The increasing trends in precipitation intensity are concentrated along the southern part of the Yangtze River while a decreasing trend is observed along the Yellow River valley. A positive trend can also be found in the Xinjiang region.

6. Precipitation persistence

The trends (d/10 yr) of the yearly maximum number of consecutive wet days (CWD) with the daily

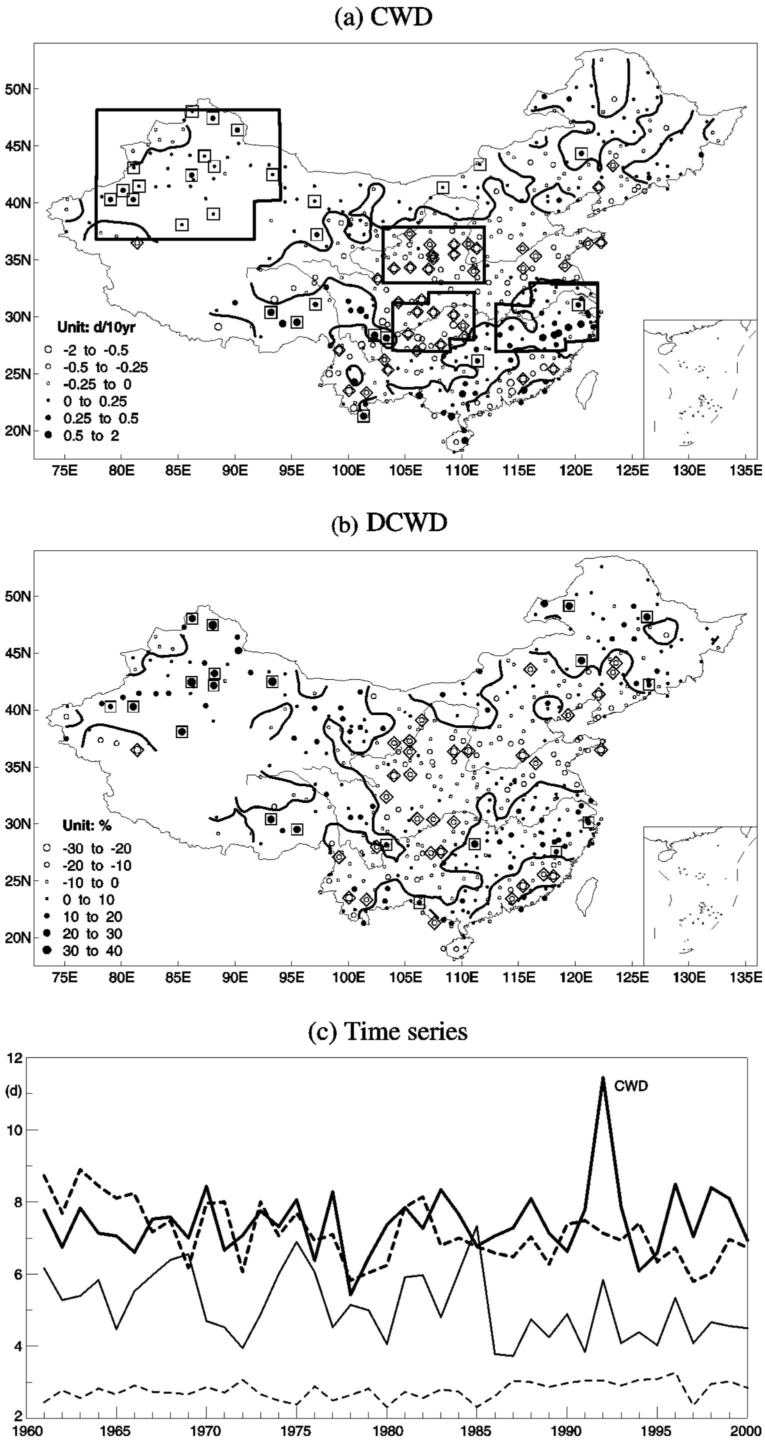

Fig. 9. Trends (units: d/10 yr) of (**a**) consecutive wet days (CWD) with the daily rainfall above 1 mm, (**b**) the ratio (units: %) of their difference between 1961–1980 and 1981–2000 in percentage, and (**c**) CWD time series in the Xinjiang region (thin dashed line), the middle Yellow River valley (thin solid line), the middle Yangtze River valley (thick dashed line) and the lower Yangtze River valley (thick solid line). Symbols and lines as in Fig. 4a

rainfall above 1 mm, and the ratio of their difference (DCWD), between 1961–1980 and 1981–2000, are shown in Fig. 9. The CWD decreased along the Yellow River valley and the upper-middle Yangtze River valley while increasing trends are observed in the Xinjiang region and southeast China except near the coast (Fig. 9a). The interdecadal change of the CWD is confirmed by the variation in these regions (Fig. 9b).

In order to examine the temporal variations of CWD in various regions, four sections were selected in Fig. 9a, and the average series inside each rectangle were calculated. Four series of CWD are plotted in Fig. 9c. In the Xinjiang region, CWD may reach a value of 4–6 days over oasis areas, while in the arid site the CWD only reaches a value of about 1–2 days. CWD in the Yellow River valley showed an abrupt decrease in 1986 and it maintained short days from that time. A decreasing trend of CWD was observed in the upper Yangtze River, while in the lower Yangtze River valley the CWD remained near a mean of about 7 days for many years, but showed a peak in 1992.

Consecutive dry days (CDD) decreased in western China but increases can be found in the southern part of North China (Fig. 10a). The ratio of the interdecadal difference of consecutive dry days showed a significant increase in the lower Yellow River valley and central southern part of China, while a decrease was observed in western China (Fig. 10b).

Persistent wet days (PWD) increased in the Xinjiang region but a decreasing trend can be found in central China (Fig. 11a). Persistent dry days (PDD) increased along the mid-lower Yellow River valley, but a decreasing trend was found in the Xinjiang region, the eastern Tibetan Plateau, and South China (Fig. 11b).

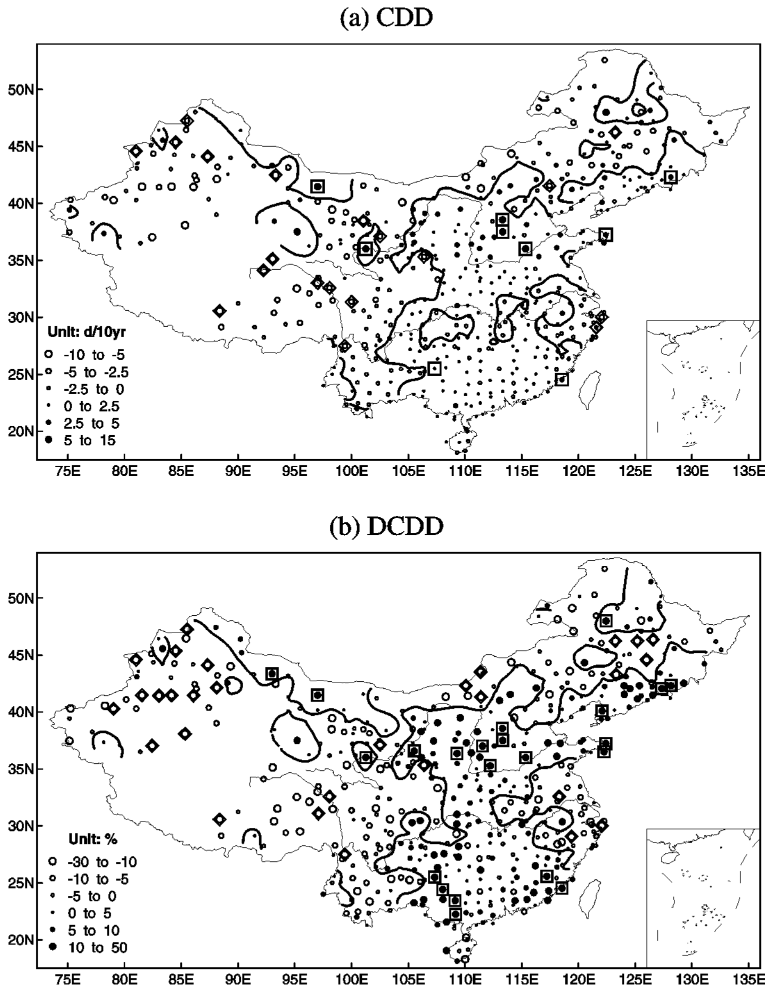

Fig. 10. Trends (units: d/10 yr) of (**a**) consecutive dry days (CDD) with the daily rainfall below 1 mm, and (**b**) the ratio (units: %) of their difference between the two periods. Symbols and lines as in Fig. 4a

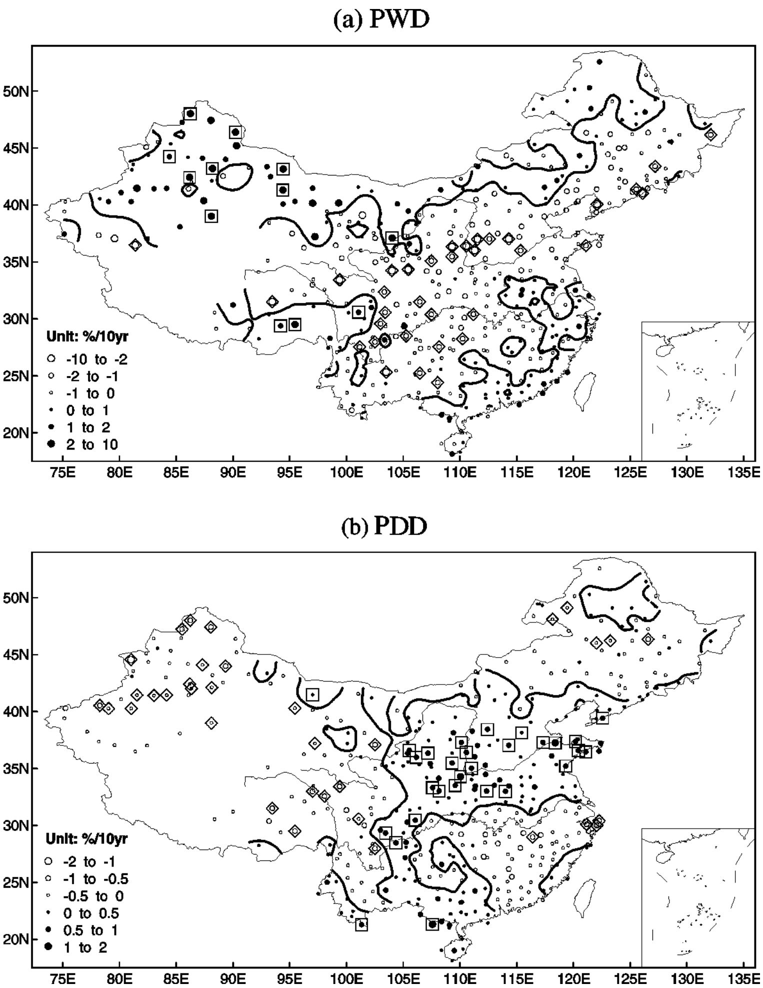

Fig. 11. Trends (units: %/10 yr) of (**a**) percentage of the sum of persistent wet days (>1 mm/d) to the sum of rain days, and (**b**) percentage of the sum of persistent dry days (<1 mm/d) to the sum of dry days. Symbols and lines as in Fig. 4a

7. Conclusion and discussion

Trends of precipitation indices during 1961 to 2000 from Chinese daily precipitation data were studied in this paper. The major conclusions, with discussions, are given as follows:

(1) Increasing trends in the number of days with daily rainfall exceeding the mean-95th percentile for 1961 to 2000 are concentrated near the mid-low Yangtze River valley. Decreasing trends are located in the upper valleys of the Yangtze River and the Yellow River. Over the last two decades, relatively large rainfalls have increased significantly in the Xinjiang region and the lower Yangtze River while decreasing trends have been found in the Yellow River valley and the southern part of northeast China. Precipitation intensity has decreased along the Yellow River valley and the middle of the Yangtze River valley while increases have been found in the Xinjiang region, the northern part of northeast China, and southeast China. Interdecadal changes in the precipitation intensity with a threshold of more than 10 mm/d is confirmed by the difference between two 20-year periods in these regions.

(2) The number of consecutive wet days has decreased along the Yellow River valley and the middle of the Yangtze River valley while an increase in the number of consecutive wet days has been found in the Xinjiang region and southeast China, except near the coast. Persistent dry days have increased along the mid-lower Yellow River valley but a decrease has been observed in western and southern China.

(3) Trends of the greatest 3 d, 5 d, and 10 d rainfall per year have increased along and in the south of the Yangtze River while a decreas-

ing trend has been identified along the Yellow River. A positive trend can also be found in the Xinjiang region.

In summary, the trends of precipitation extremes in China show three different regions or zones. A zone with a decreasing trend of precipitation extremes was observed from the southern part of northeast China to the mid-low Yellow River and the upper Yangtze River. On the other hand, increasing trends of precipitation extremes have been found in the Xinjiang region (northwest China), the northern part of northeast China, and southeast China, mainly to the south of the mid-low Yangtze River. These extremes have contributed to the increase in floods in southeast China and the Xinjiang region and increased drought along the Yellow River valley in the last two decades. It was noted that regional trends of extreme indices were consistent with the two large gradient zones of annual mean precipitation along 200–400 mm and 1000–1400 mm. Regional trends were also found in areas with large precipitation variations, except in desert regions (see Fig. 1b to Fig. 3).

It is noted that increases/decreases in the mean and the variance of daily temperature and daily precipitation can change the probability of extreme climate occurrence. Other possibilities are an increase/decrease in the frequency of extreme events without there being a net trend in precipitation or that changes in precipitation are not associated with extremes (Karl and Knight, 1998). Precipitation extremes were confirmed by the climate transition from one state to another (Shi et al, 2003). Annual temperature showed an increasing trend in northern China but a cool-summer trend observed along the mid-low Yangtze River valley (Fig. 12). Figure 12 also shows that the annual precipitation was mainly contributed to by summer rainfall, so that a warm-wet state was observed in northwest China and the northern part of northeast China. A warm-dry state was found to be situated in the southern part of northeast China and along the

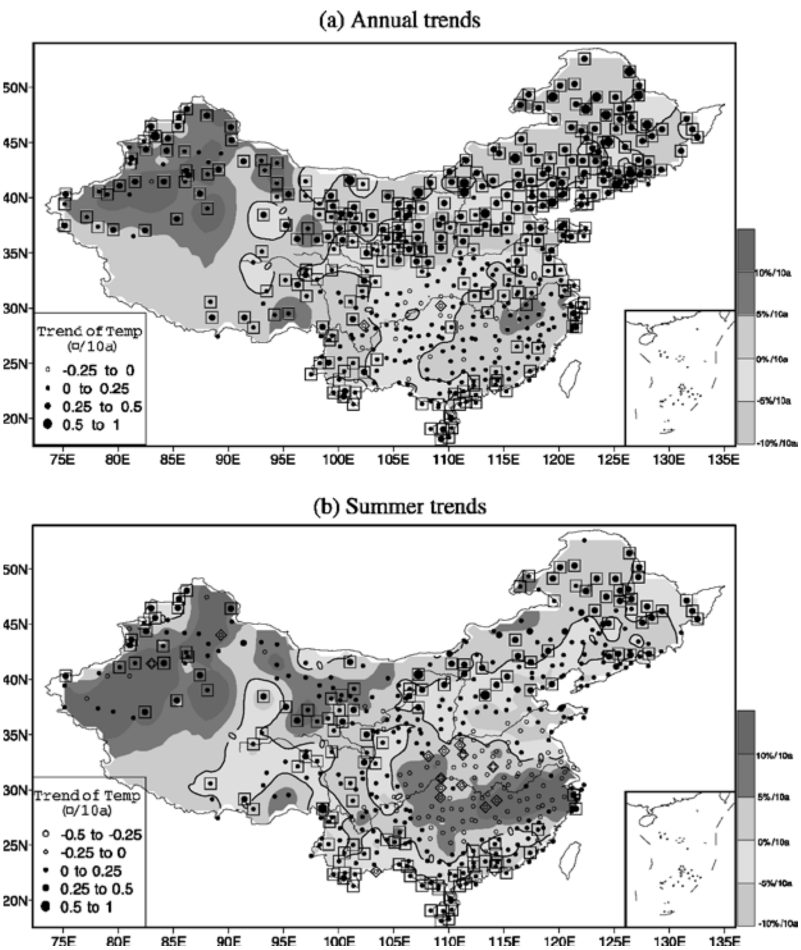

Fig. 12. Trends of temperature (°C/10 yr) and percent precipitation (%/10 yr) for 1961 to 2000 in (**a**) annual total, and (**b**) summer (JJA) mean. Dots and open circles indicate the increasing trend and decreasing trend of temperature, respectively. Shaded areas indicate the increasing trend and decreasing trend of precipitation. Symbols and lines as in Fig. 4a

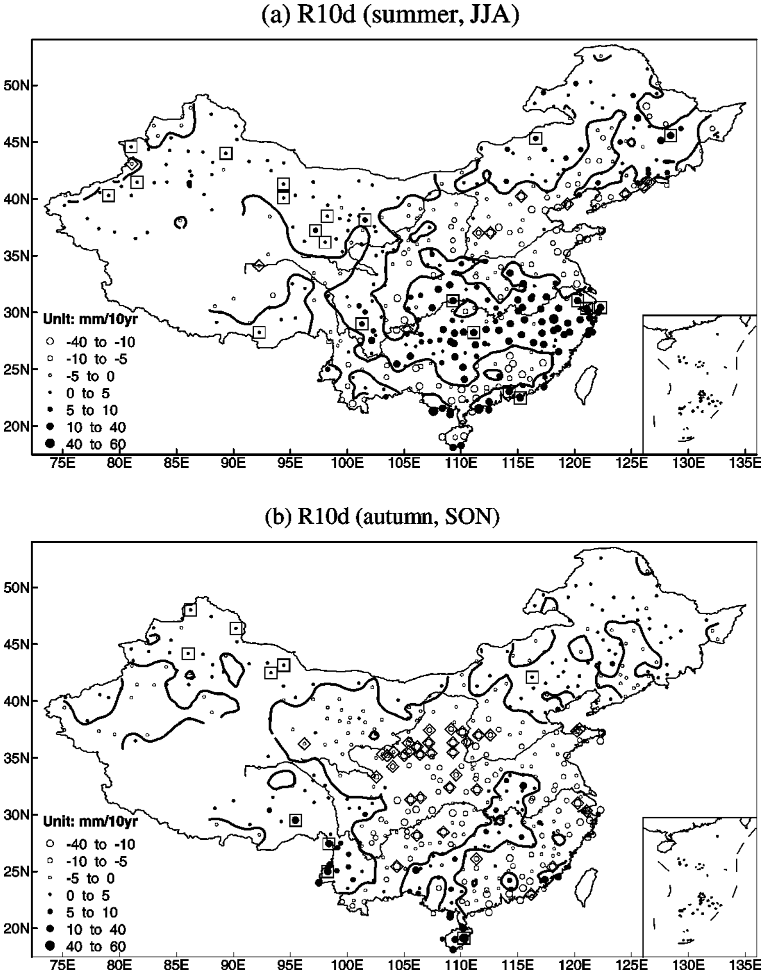

Fig. 13. Trends (units: mm/10 yr) of the greatest 10-day rainfalls per year for (**a**) summer (JJA), and (**b**) autumn (SON). Symbols and lines as in Fig. 4a

Yellow River valley, while a cool-wet summer was found in southeast China, particularly in the mid-low Yangtze River valley. The trends in precipitation extremes in the three different zones in China coincide with the trends of annual precipitation and summer precipitation.

A detailed analysis of the seasonal trends from various precipitation indices was also conducted. Figure 13 shows the trends of the greatest 10 d rainfalls in summer and autumn for 1961 to 2000. In summer, an increasing trend was mainly concentrated along the Yangtze River valley and decreasing trends can be observed in the mid-low Yellow River valley and in the south coast of China. In autumn, decreasing trends of the greatest 10 d rainfalls were located in central China over the mid Yellow River, as well as the upper and lower Yangtze River. The trend distribution of the greatest 10 d rainfalls in summer was similar to that of annual distribution (see Fig. 8c). Trends of the greatest 10 d rainfalls in summer had a contribution in phase with the summer mean precipitation (see Fig. 12b). Other indices such as R90N, R10 mm, SDII, R5d, CWD, CDD, PWD and PDD, in summer and autumn, had a similar contribution to the annual ones. It was concluded that the trend of dry-extreme indices was found in the Yellow River valley and North China while the trend of wet-extreme indices was observed in the mid-low Yangtze River valley during summer to autumn.

Extreme events, particularly for precipitation, are a random signal in the climate record and a time series of only 40 years may be a little short for a robust trend analysis, but some indices in this study, based on percentiles and those modified thresholds, can be good indicators for climate extremes in China. Extremes and their trends show a strong correlation with the change of the mean climate state. Regional precipitation extremes and their explanation for climate change should be interesting for China and for the rest of the world.

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