Trends in Total Precipitation and Frequency of Daily Precipitation Extremes over China

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ABSTRACT

Based on a newly developed daily precipitation dataset of 740 stations in China and more robust trend detection techniques, trends in annual and seasonal total precipitation and in extreme daily precipitation, defined as those larger than its 95th percentile for the year, summer, and winter half years, have been assessed for the period 1951–2000. Possible links between changes in total precipitation and frequency of extremes have also been explored. The results indicate that there is little trend in total precipitation for China as a whole, but there are distinctive regional and seasonal patterns of trends. Annual total precipitation has significantly decreased over southern northeast China, north China, and over the Sichuan Basin but significantly increased in western China, the Yangtze River valley, and the southeastern coast. In western China, precipitation increase has been observed for both cold and warm seasons. However, trends differ from one season to another in eastern China. Spring precipitation has increased in southern northeast China and north China but decreased significantly in the midreach of the Yangzte River. The summer precipitation trend is very similar to that of annual totals. Autumn precipitation has generally decreased throughout eastern China. In winter, precipitation has significantly decreased over the northern part of eastern China but increased in the south. The number of rain days has significantly decreased throughout most parts of China with northwest China being an exception. Meanwhile, precipitation intensity has significantly increased. This suggests that the precipitation increase in western China is due to the increase in both precipitation frequency and intensity. In eastern China, the impact of reduced number of rain days seems to be more dominant in the north while the influence of enhanced intensity prevails in the south. Over regions with increasing precipitation trends, there have been much higher than normal frequency of precipitation extreme events. For example, significant increases in extreme precipitation have been found in western China, in the mid–lower reaches of the Yangtze River, and in parts of the southwest and south China coastal area. A significant decrease in extremes is observed in north China and the Sichuan Basin. Trends in the number of extremes and total precipitation from nonextreme events are generally in phase. An exception is southwest China where an increase of extreme events is associated with a decrease in total nonextreme precipitation.

1. Introduction

China is located in east Asia (Fig. 1). Because of large landmass and various climate regions, weather and climate extremes bring frequent damage to the country. For example, floods in 1998 caused $36 billion in economic losses and more than 3000 lives in the Yangtze River valley in southern China and in the Nenjiang–Songhuajiang valley in northeast China [the National Climate Center (NCC) 1998]. Since 1985 the Yellow River, the second largest river in China, has frequently dried up; thus, river discharge is interrupted in some places. A severe drought over north China in 1997 resulted in a 226-day dry up period for the Yellow River. These extreme conditions are all related to the variation of total and extreme precipitation.

The various climates of China are decisively determined by the winter and summer monsoon (Domroes

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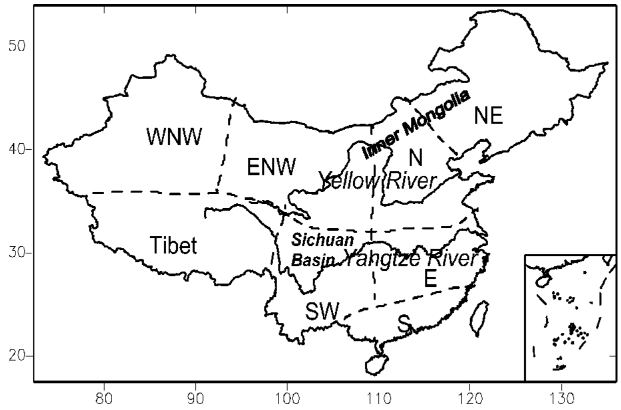

FIG. 1. Schematic map of China with geographic regions mentioned in the text. Northeast, north, eastern northwest, and western northwest China are marked by NE, N, ENW, and WNW, respectively. These four regions constitute northern China. Southwest, east, and south China are marked by SW, E, and S, respectively. Together they are called southern China.

and Peng 1988). The monsoon system together with the effects of topography yields a remarkable change in annual total precipitation, from less than 25 mm in the remote northwest to more than 2000 mm in the southeast. The climate in western China is generally very dry, but it is mainly semihumid and humid in the eastern part of the country. The main rainy season in eastern China corresponds with the progress of the east Asian summer monsoon. At the first stage, the major rain belt stagnates over south China in May–early June, over central China from 20 June to 10 July, and over north China from 5 to 25 August. From midsummer onward, the major rain belt rapidly retreats southward. Over about 20 days, it retreats from mainland China (Gao and Xu 1962; Ding 1994). The summer monsoon rainfall brings a necessary water supply for growing crops to nourish more than a billion people. As such, variability and change in precipitation amounts and extreme precipitation are major concerns for both the Chinese government and the general public.

Changes in total and extreme precipitation have attracted much attention in recent years. The Intergovernmental Panel of Climate Change (IPCC) in its recent Assessment Report (Houghton et al. 2001) presents a global picture of trends in precipitation during different periods. China is a noticeable data-sparse area for that global map, even for the period 1976–99. There are a couple of recent studies that document precipitation changes in China. Zhai et al. (1999) analyzed the trend in normalized annual precipitation anomalies and in some annual extremes for the period 1951–95 for 361 stations in China. They suggested that changes in extreme and total precipitation might be closely related. Using pentad precipitation data for 1960–96 at 330 stations in China, Ren et al. (2000) showed an increasing trend in summer precipitation over the mid lower reaches of the Yangtze River and a decrease trend over the Yellow River basin, but almost no change in the high-latitude areas. Those studies are limited in their scope and data use. Their results also need to be reexamined since the statistical significance of trends was not rigorously assessed. This study provides a more thorough account and update of changes in both total and extreme precipitation in China over the second half of the twentieth century, not only on annual and but also on seasonal bases. We use a newly developed higher-quality dataset that provides a much denser network and covers a longer period. We also employ more robust and sounder trend detection techniques. Moreover, links between changes in total and extreme precipitation are also investigated. The paper is organized as follows. We describe the datasets and analysis techniques in section 2. Trends in the total precipitation and the frequency of extreme events are presented in sections 3 and 4, respectively. The connection between them is shown in section 5. We conclude with a discussion in section 6.

2. Data and methods

a. Data preparations

A dataset of daily precipitation amounts at 740 stations along with detailed metadata covering mainland China for the period 1951–2000 has been used in this study. It includes almost all first- and second-class national climate stations in China and was developed at the Climate Data Center (CDC) of the National Meteorological Center of the China Meteorological Administration. This is the best daily dataset currently available for studying climate change in the country. The data have been subject to quality control procedures of the CDC. Missing values and temporal inhomogeneity are screened before the data are used in the subsequent analysis. Stations with too many missing values are dropped. A year is considered to be missing if there are more than 10% missing days in the year. A station is retained only if it has more than 40 nonmissing years of data. A total of 611 stations passed this process. After checking the availability of data, we examine the possible inhomogeneity problem. Liu and Sun (1995) studied temporal inhomogeneity in China's precipitation data. They found that inhomogeneity was a problem for some stations located in northwestern China where the precipitation amount is small and the wind is strong. Inhomogeneities are mainly caused by station relocation. In this study we adopt the two criteria of Zhai and Ren (1999) to identify stations with relocation problems. Relocation is deemed to have made the data inhomogeneous if the location of the station was moved more than 20 km or if the elevation of the rain gauge experienced a change of more than 50 m. After this procedure, 530 stations were retained for the subsequent trend analysis.

b. Analysis techniques

In China, heavy and severe storm rains are extremes and are traditionally defined as events with daily precipitation amounts greater than 25, 50, and 100 mm, respectively (Domroes and Peng 1988). These events may cause a variety of damage and the criteria have been used by engineers and officials as indicators of possible flood severity. In most parts of China, however, severe storm rain events are very rare. Because of low precipitation, even heavy precipitation events are very rare in the vast western region of China. To assess trends in extreme precipitation events across the country, we compute trends in the number of relative extreme events defined as the days with daily precipitation amount greater than the 95th percentile of all rain days during 1961–90. These days are referred to as extreme precipitation days. The idea of examining trends in such relative extreme events has been widely explored in recent studies (e.g., Frich et al. 2002; Manton et al. 2001).

To provide a single value for the entire country for a particular quantity, we compute an area-weighted average for the variable. In doing so, we first divide the country into 2° × 2° boxes and then calculate box values as the arithmetic mean of all available station data in the box. Afterward, we use box values to compute the national average by taking the areas of boxes as weights.

Trends in total precipitation are estimated using Kendall's tau-based slope estimator (Sen 1968). This method is nonparametric and does not assume the distributional form for the data under investigation. In addition, it is not sensitive to outliers. The possible autocorrelation in the time series that may render the test of statistical significance of a trend unreliable was taken into account by using an iterative procedure introduced by Zhang et al. (2000) and refined by Wang and Swail (2001). Monte Carlo simulation indicates that this procedure is more proper for trend detection (Zhang and Zwiers 2004). We use the procedure outlined in Wang and Swail (2001, see their appendix A). The statistical significance of the trend was assessed at the 5% level.

The number of extreme events does not follow a normal distribution. It is therefore not appropriate to use a linear regression. A nonparametric method, such as Kendall's tau-based slope estimator, could be used. However, if the distributional form is known, a parametric method usually has a better test power. Frei and Schar (2001) suggest that the number of heavy precipitation events follows a binominal distribution and its trend may be estimated with a logistic regression, a special form of generalized linear models (GLM) (Lindsey 1997). Following Frei and Schar (2001), we use logistic regression to estimate the trend and its statistical significance for the frequency of heavy and extreme events. We also employ logistic regression to identify a possible link between the changes in frequency of precipitation extremes and in total precipitation at a station. A short description of logistic regression is given in the appendix. A detailed application of logistic regression for detection of trends in extreme events and its power of detection can be found in Frei and Schar (2001).

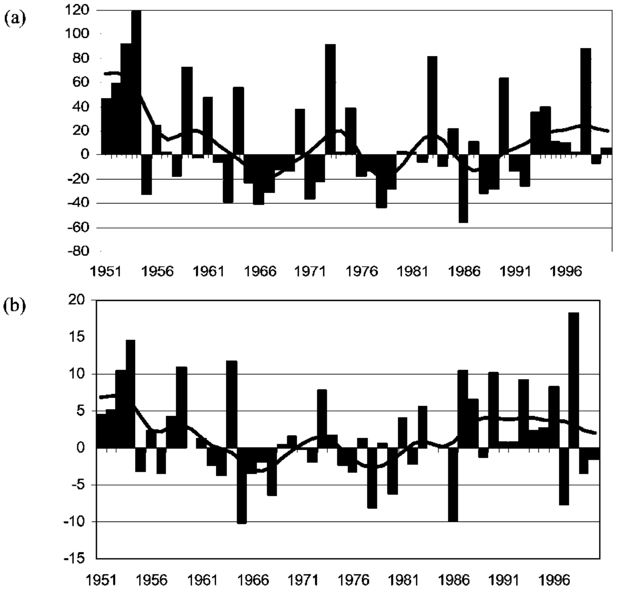

FIG. 2. (a) Area-averaged time series of annual precipitation anomalies (in mm) and (b) normalized annual precipitation anomalies (in percentages) for China. Bars represent annual values while solid curves are moving averages computed from an 11-yr binomial filter.

First, trend analyses are conducted on annual and seasonal bases. The standard four seasons are used when computing seasonal time series. This allows comparison of the results with those published for other parts of the world for the seasons. The major rainy season in China, especially in east China does not follow the climatological seasonal boundaries. One may argue that the use of standard seasons would unavoidably break the natural rainy seasons, making the analytical results less meaningful. We therefore calculate trends for wet and dry half years as well. Domroes and Peng (1988) showed that the number of wet months varies from seven to three across the country and is between four and five at the majority of stations. Precipitation is generally concentrated during April–September (Bao 1987). We use those six months as the warm (wet) half year and October–March as the cold (dry) half year.

3. Trends in precipitation totals

a. Annual precipitation

The time series of area-weighted annual precipitation anomalies relative to the 1961–90 mean value for China

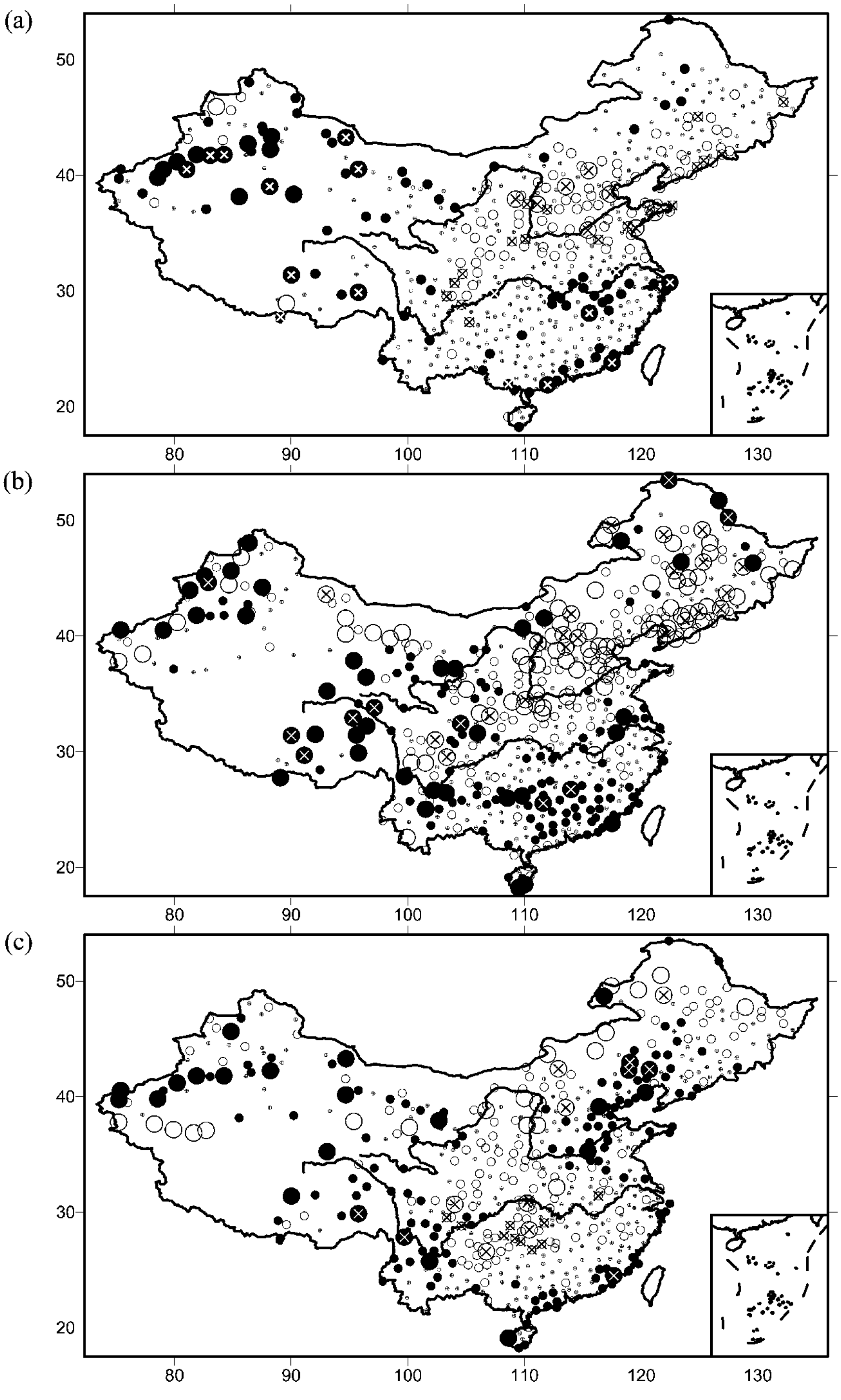

FIG. 3. Spatial distribution of trends for (a) annual, (b) winter, (c) spring, (d) summer, and (e) autumn normalized precipitation anomalies during 1951–2000. The solid (open) circles indicate increasing (decreasing) trends, respectively. Trends that are larger than 7.5% decade^{-1}, between 7.5% and 2.5% decade^{-1}, and less than 2.5% decade^{-1} are marked by large, middle, and small circles, respectively. Those significant at the 5% level are marked by crosses (×).

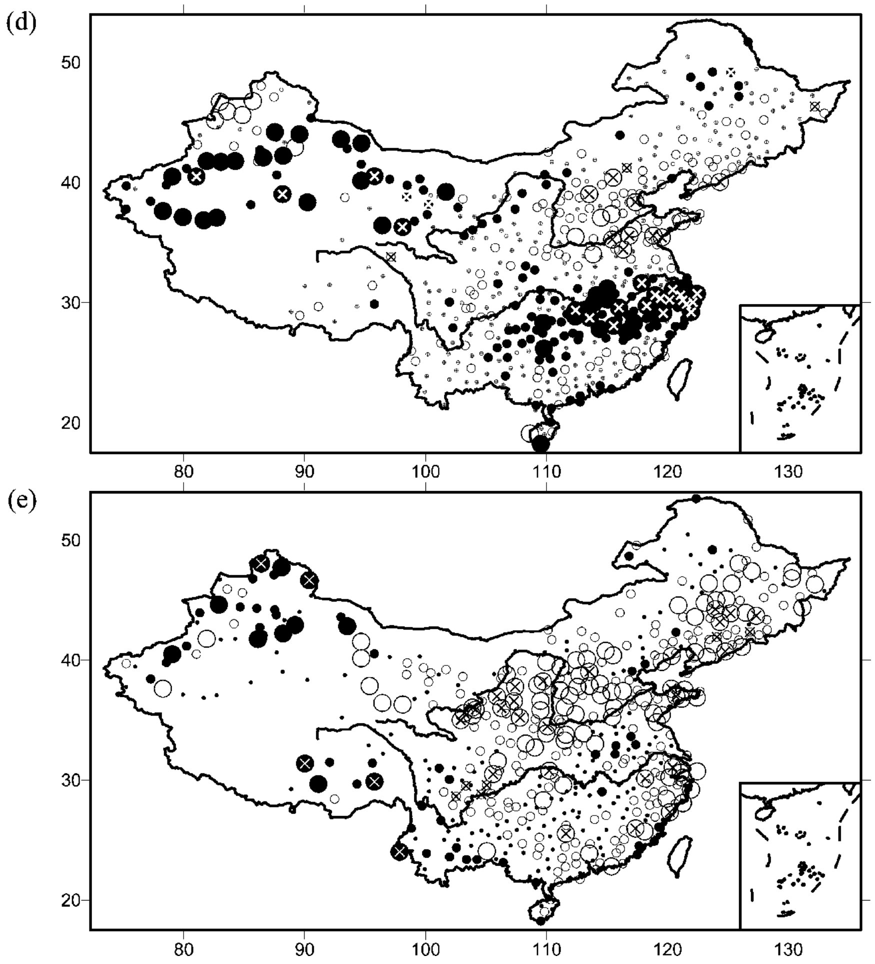

FIG. 3. (*Continued*)

is shown in Fig. 2a. The most striking feature of it is strong variability at both interannual and interdecadal scales. For example, the years 1954, 1998, 1973, and 1983 were very wet, while the years 1978 and 1986 were very dry. The period from the 1950s to the early 1960s and 1990s was generally wet, but the period between the 1960s and 1970s was mostly dry. Though the total precipitation amounts give a good measure of total precipitation in the country, their time variations actually reflect more of precipitation variability over southern and eastern China since these areas have much larger weights due to higher precipitation amounts. To avoid this problem, in Fig. 2b we provide a time series of area-weighted normalized precipitation anomalies defined as precipitation anomalies scaled by the precipitation normal at the station.

The two time series shown in Figs. 2a and 2b are similar in general, especially at the decadal time scale, but there are apparent differences on a year-to-year basis. For example, the years 1973 and 1983 stand out in Fig. 2a as very wet years, but they are not particularly wet in Fig. 2b. However, the very wet years 1954 and 1998 are very remarkable in both diagrams. This suggests that the floods were severe in 1973 and 1983 but on a much smaller spatial scale if compared with those in 1954 and 1998. In fact, the floods in 1954 and 1998 were the most severe ones influencing the largest areas over the country in the past 50 years (NCC 1998).

The averaged annual total precipitation anomalies show a decreasing trend at a rate of 1.03 mm decade^{-1}. This is generally consistent with an earlier result indicating a small downward trend during 1951–95 estimated from a dataset of 296 stations (Zhai et al. 1999), suggesting that adding the most recent 5 years does not alter the precipitation trend. The decreasing trend is too small to be statistically significant, however. The averaged normalized annual precipitation anomalies give a slightly upward trend at 0.24% decade^{-1}. This trend is also not significant. The difference in the signs of the trends in the two time series is caused by the different ways of averaging, suggesting regional differences in precipitation changes. For example, the averaged annual precipitation anomalies were particularly large in the late 1950s, indicating higher precipitation,

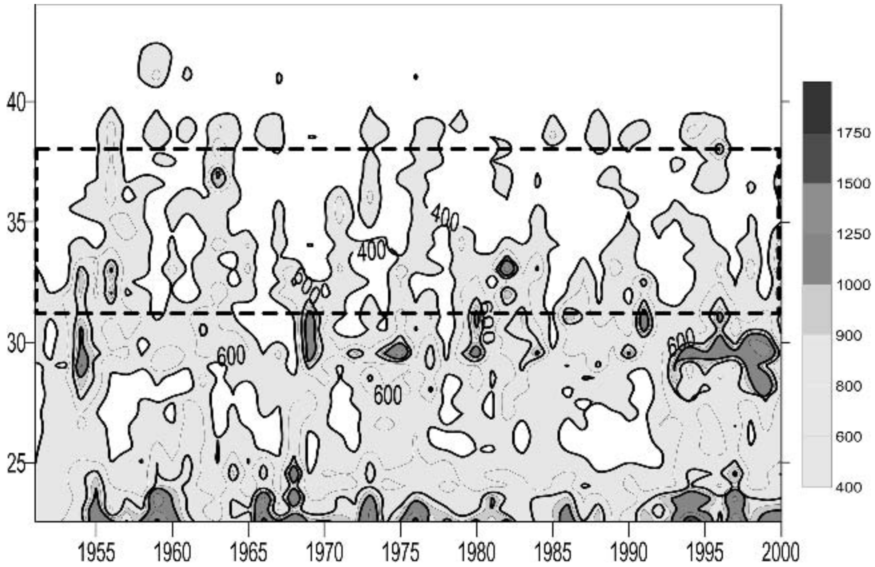

Fig. 4. Time series of summer [Jun–Aug (JJA)] precipitation (in mm) over eastern China along a 115°E section. White areas indicate rainfall amount less than 400 mm. The two dashed lines indicate the locations of Yangtze River valley (south) and north China (north).

especially the abundant rain in the Yangtze River in the mid-1950s. On the other hand, persistent large values of normalized precipitation anomalies appeared after the late 1980s, reflecting a stronger increase in northwest China, which will be discussed later. Overall, there is no apparent trend in total precipitation over China, no matter how the averages are computed. This differs from the trend results for many other midlatitude regions in the Northern Hemisphere. Annual total precipitation in North America increased (Groisman and Easterling 1994; Zhang et al. 2000) in the twentieth century.

Annual precipitation does not show any significant trend for China as a whole; however, there are distinctive regional patterns. Figure 3a displays the spatial distribution of trends in normalized annual precipitation anomalies. Annual total precipitation has increased by 10%–20% decade^{-1} in most parts of northwestern China, by 5%–10% decade^{-1} in Tibet, and by 5% or less decade^{-1} in the southeast coast and the mid lower reaches of the Yangtze River. It has decreased elsewhere, by about 5% decade^{-1}, with the most significant decrease in north China and the Sichuan Basin.

b. Seasonal precipitation

The spatial patterns of trends in precipitation for winter (Fig. 3b) and summer (Fig. 3d) are similar to that for the annual one. For winter precipitation, significant positive trends are observed over Tibet and small parts in southern China, and significant negative trends are observed over most parts of northeast, north, and eastern-northwest China, and the Sichuan Basin. Compared with annual trends, winter precipitation shows dramatic decreases over Inner Mongolia. For summer precipitation, significant increasing trends appear in the lower reaches of the Yangtze River and western China, and significant decreasing trends appear over north China.

Spring precipitation has increased in many parts of western and southwest China, and the southeast coast where the trends show the same signs as those for the annual total. However, in the other parts of eastern China, the trend is generally opposite to that of annual totals. For example, spring precipitation has decreased in southern-northeast and north China, and in the mid lower reaches of the Yangtze River (Fig. 3c). Most parts of the Northern Hemisphere midlatitudes have experienced an increase in precipitation during autumn and winter (Houghton et al. 2001), but China is quite different. Autumn precipitation has decreased in China except over small parts of western China. This has resulted in a decrease in the famous "autumn rain" phenomena in central and southwest China. Summer is the wettest season, its precipitation accounts for 50%–70% of annual totals in most parts of the country. This may explain the similarity between annual and summer spatial patterns of trends. In particular, it appears that the upward trend in annual totals over the mid lower reaches of the Yangtze River is mainly due to an increase of summer precipitation in the region. To provide more details of the summer precipitation variation in eastern China, in Fig. 4 we plot the time series of summer precipitation for a cross section along 115°E. Before the 1970s, summer precipitation was almost always over 400 mm in north China (north of 35°N). After the 1970s, it has rarely been over 400 mm. At the

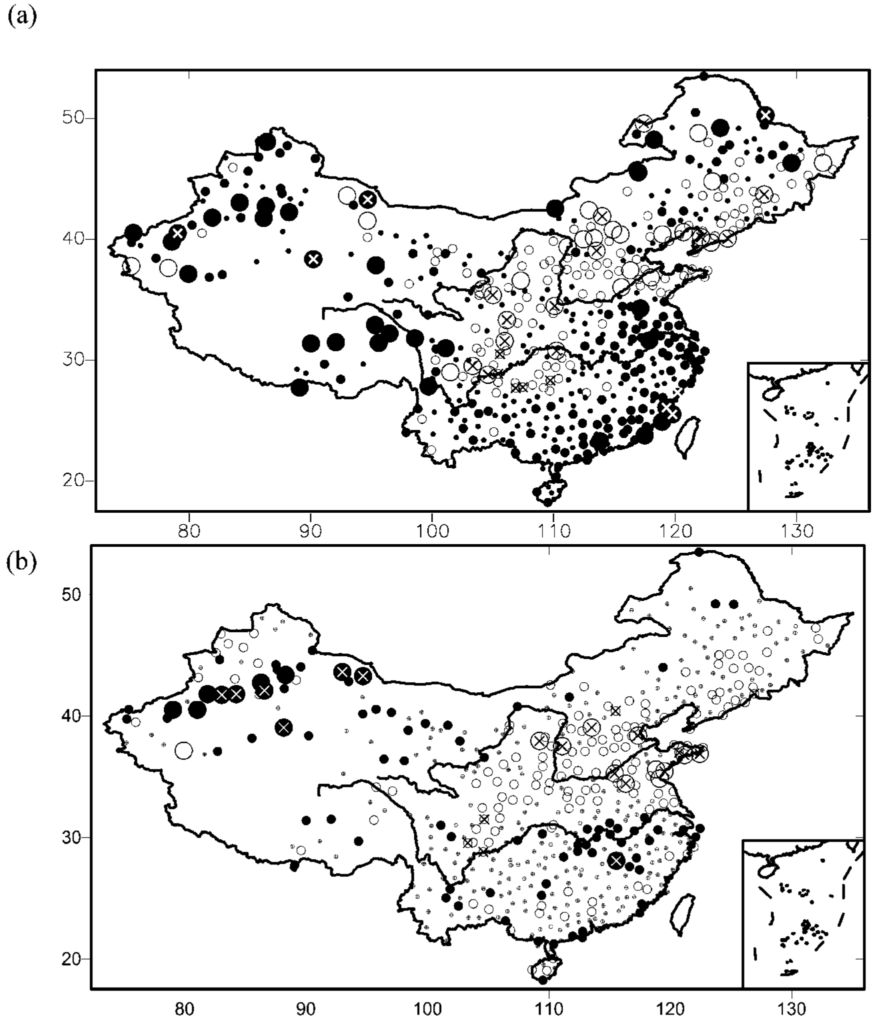

FIG. 5. As in Fig. 3 but for (a) cold and (b) warm half years.

same time, a very heavy rain belt persisted in the south, especially south of the Yangtze River (south of 30°N) during the 1990s. Gong and Ho (2002) found a similar shift in the summer rainfall over the Yangtze River valley, and Ho et al. (2003) show similar change in Korean precipitation. Such changes in summer precipitation over eastern China and Korea likely resulted from changes in the east Asian summer monsoon system. They have caused more floods in the south, such as the floods in 1980, 1983, 1986, 1987, 1991, 1993, and 1998 in the Yangtze River valley, more frequent droughts in the north (Wang and Zhai 2003), and more frequent dry up of the Yellow River. Wang (2001) indicated that there was a weakening of the Asian monsoon circulation after the 1970s. Zhao and Xu (2002) suggested an association between changes in sea surface temperature anomalies in the equatorial eastern Pacific, in wintertime snow cover over Tibet, and in the monsoon system and precipitation anomalies. Gong and Ho (2002) attributed the sudden increase of summer rainfall over the Yangtze River valley to the change in the subtropical high over the northwest Pacific. The variation of the subtropical high is closely related to the variations of sea surface temperature in both the eastern tropical Pacific and the tropical Indian Ocean. Based on data from China, Korea, and Japan, Qian et al. (2003) suggest that such a change could be linked to the multidecadal variation of monsoon circulation in east Asia. In our study, however, it should be pointed out here that Fig. 4 seems to suggest a tendency of southward shift of the summer rain belt over eastern China rather than a sudden jump as discussed in other studies.

c. Precipitation in cold and warm half years

The spatial patterns of precipitation trends for the cold and warm half years are very similar to that of annual precipitation (Fig. 5). Precipitation increased in both cold and warm halves of the year in western China, with larger increases in terms of percentage in cold half years due to smaller total precipitation.

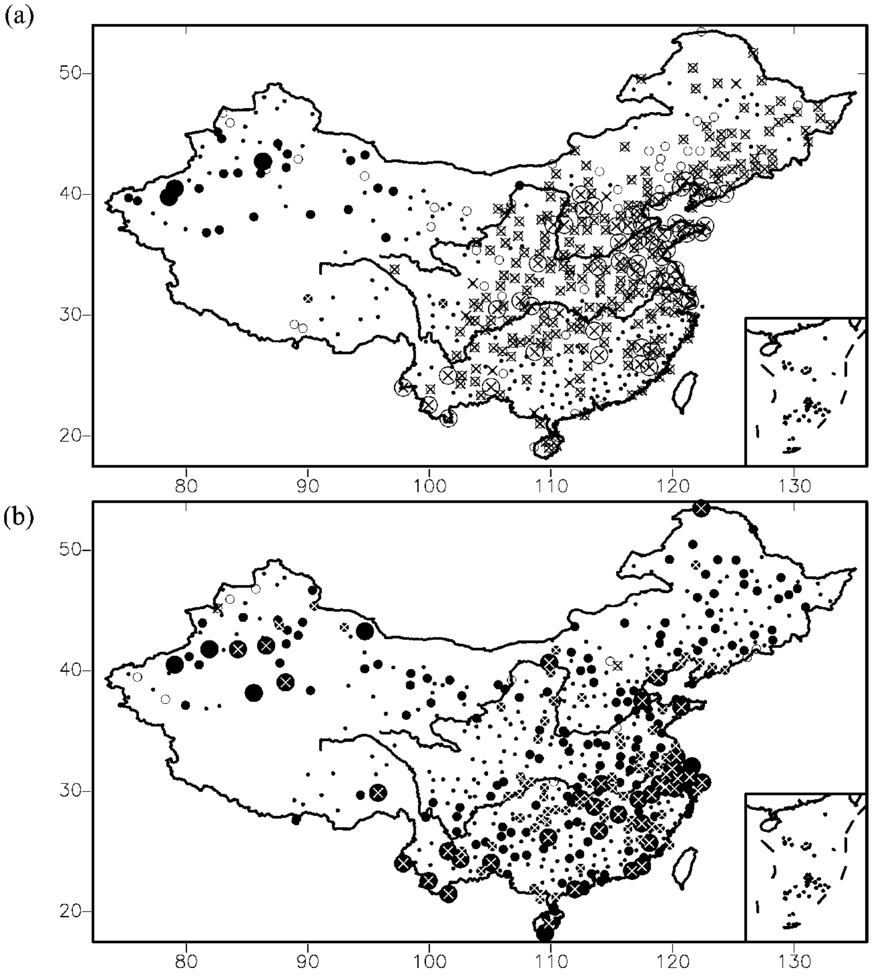

FIG. 6. Trends in the (a) annual number of rain days and (b) annual average of daily rainfall during rain days. Units are percentage change over the corresponding 1961–90 averages. Solid (open) circles indicate increasing (decreasing) trends, respectively. Trends larger than 7.5% decade^{-1}, between 7.5% and 2.5% decade^{-1}, and less than 2.5% decade^{-1} are represented by large, middle, and small circles, respectively. Trends significant at the 5% level are marked by crosses (×).

In eastern China, trends show similar patterns for both cold and warm halves of the year. In the cold half, precipitation has increased in the lower reach of the Yangtze River and south China, and decreased in eastern-northeast and north China and the area from the Yellow River to the middle reach of the Yangtze River. Decreased trends are significant over northern north China and the Sichuan Basin (shown in Fig. 5a). In the warm half year (Fig. 5b), precipitation decreased in large areas from eastern-northeast China, through north China to the Sichuan Basin, in part of south China, and northwestern Tibet. North China has experienced the most significant and largest percentage of decreasing trends in precipitation, while the Yangtze River valley has shown increases due to the increases in the summer season.

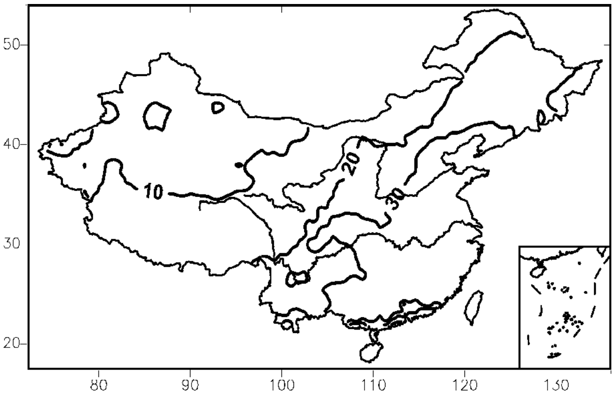

FIG. 7. The 95th percentiles of daily precipitation during 1961–90. Unit is 1 mm day^{-1}.

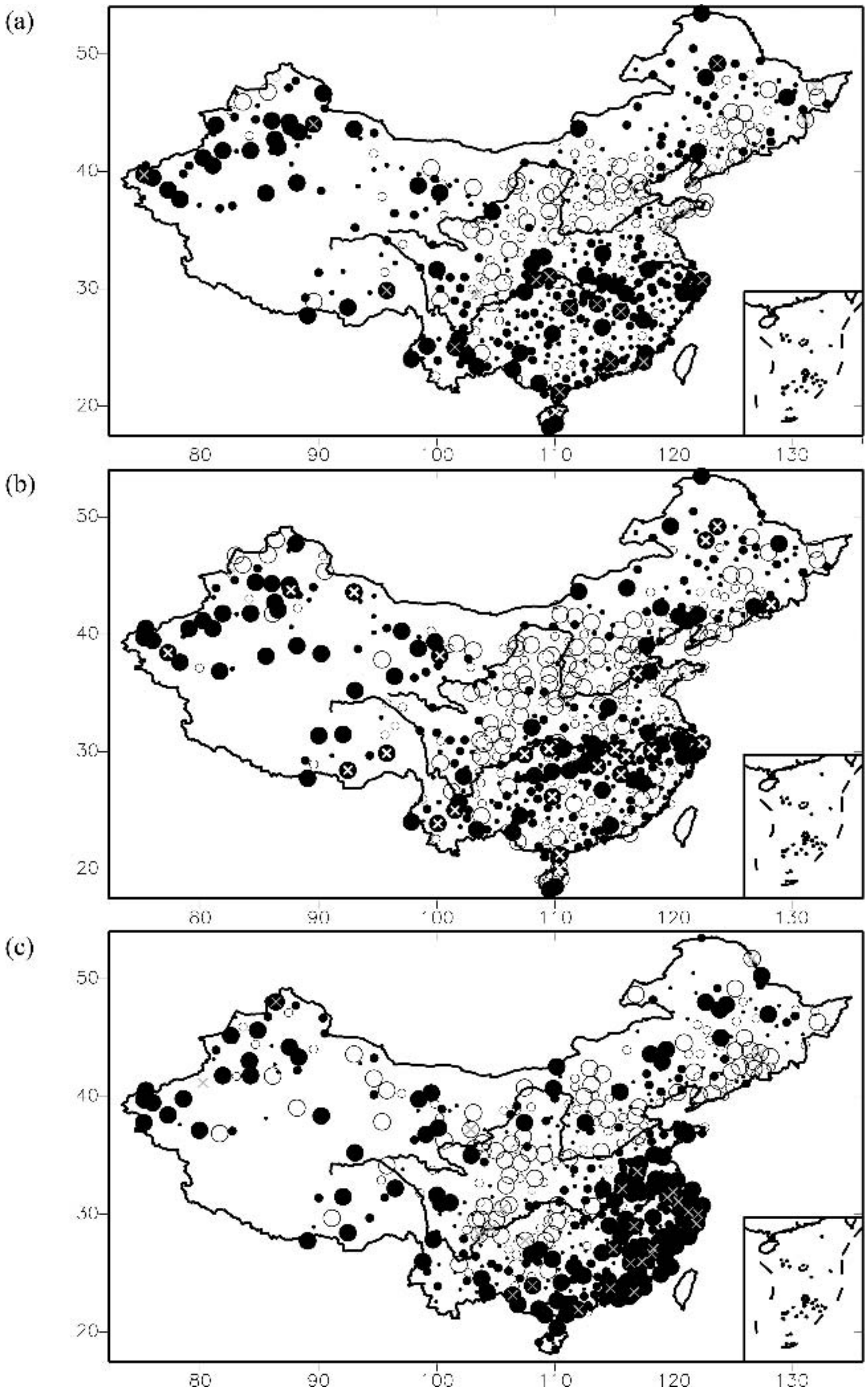

FIG. 8. Trends in the frequency of extreme precipitation days for (a) annual, (b) warm half year, and (c) cold half year series, respectively. Solid (open) circles indicate increasing (decreasing) trends, respectively. Trend scales are equivalent to those in Fig. 6.

d. Trends in the number of rain days and rainfall intensity

Trends in total precipitation may be caused by changes in the frequency of rain days and/or in the average intensity of precipitation. To better understand which of the above factors contributes to the trends in annual precipitation, we computed trends in the annual time series of the number of rain days, and of the average daily precipitation during rain days. The two time

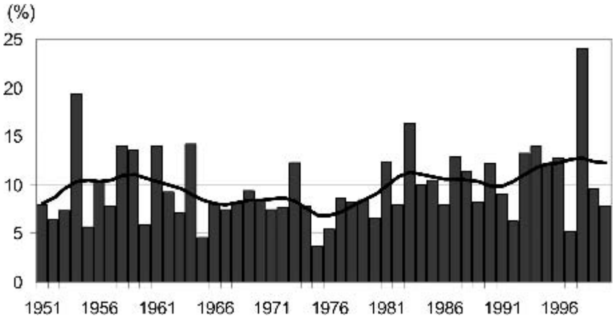

FIG. 9. As in Fig. 2 except for variations of percentage of areas in China that experienced much above normal occurrence of precipitation extremes.

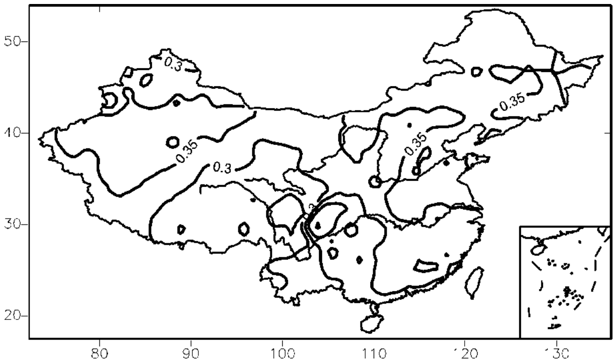

FIG. 10. The fraction of extreme precipitation to annual totals.

series were normalized before being used for computing trends.

Figure 6 shows the trends in these two quantities. Except in western China, the number of rain days has significantly decreased. This proves an earlier discussion of Zhai et al. (1999) that the precipitation frequency may have decreased. The average daily rain rate has significantly increased over almost the entire country. These suggest that in most parts of China, while precipitation is getting less frequent, it is more intense. The increase in total precipitation in the mid lower reaches of the Yangtze River and the southeast coast is generally due to the increase of precipitation intensity. The decrease in total precipitation in northern China is the result of a great decrease in the number of rain days such that an increase in the average intensity was not able to compensate the loss of precipitation due to fewer rain days. In western China, however, the increase in total precipitation over western China seems to be due to an increase in both precipitation frequency and average intensity.

4. Trends in the occurrence of extreme precipitation

Figure 7 displays the 95th percentiles of daily precipitation during 1961–90. These percentile values are the thresholds used for defining extreme precipitation days. They range between 20 and 40 mm in most parts of east China. In some regions, such as the southeast coast, and lower reaches of the Yangtze, they can be over 40 mm. They decrease to 10–20 mm in most parts of central and eastern Inner Mongolia, eastern-northwest China, and Tibet and become less than 10 mm in western-northwest China.

The trends in the annual frequency of extreme precipitation days (Fig. 8a) have similar spatial distribution to that of annual total precipitation (Fig. 3a). Decreasing trends appear over eastern-northeast and north China, and the Sichuan Basin. Statistically significant downward trends are found in both north China and the Sichuan Basin. Increasing trends are mainly located over western China and the mid–lower reaches of the Yangtze River and the regions to the south with trends statistically significant at the 5% level over the mid lower reaches of the Yangtze River and parts of southwest China and the south China coastal area.

The spatial distribution of trends for the warm half year resembles that of the annual time series because most of the extreme precipitation occurs in this half year. The pattern for the cold half year (Fig. 8c) is not dissimilar to that of the annual time series, with an exception that more stations in southern China show significant increasing trends.

To provide an overall view of past changes in extreme precipitation across the country, we computed an extreme precipitation index similar to the one described in Karl et al. (1996). The top 10% of years with frequency of extremes from 1951 to 2000 are considered as years with much above normal frequency of extreme precipitation. The proportion of a 2° × 2° box affected by extremes is calculated as the ratio of the number of stations with above normal extremes divided by the total number of stations in the box. These box values are averaged using the box areas as weights to derive a national extreme precipitation index that aggregates climate change information from station data in the country. The index is shown in Fig. 9. It indicates that 24% and 19% of mainland China experienced much above normal occurrence of precipitation extremes during 1998 and 1954, the years with very severe floods in the country. Note that this index also suggests an increasing trend in the proportion of China affected by extreme precipitation.

5. Connection between changes in extreme and total precipitation

The above analyses indicate great similarity between the spatial patterns of trends in extreme and total precipitation. These may suggest a close linkage between changes in extreme and total precipitation. In fact, the frequency of extreme precipitation is positively correlated with total precipitation at almost all stations

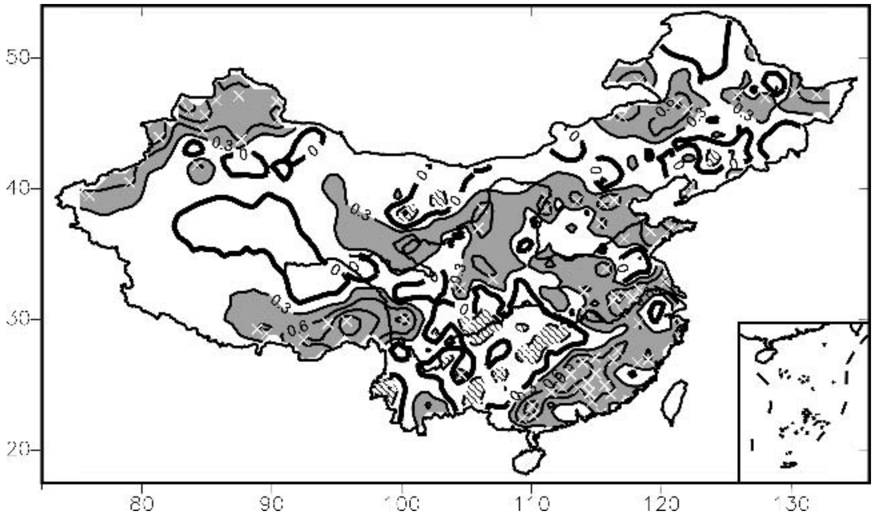

FIG. 11. Logistic linear regression coefficients between frequency of annual days of extreme precipitation and normalized precipitation totals fallen in nonextreme rain days over China. Positive (negative) values represent positive (negative) relationships. Gray areas indicate regression coefficients greater than 0.3 while line-filled areas show regression coefficients less than 0.3. Crosses (×) indicate the area with statistical significance at the 5% level.

across the country (not shown). This is not surprising since extreme precipitation typically accounts for 30%–40% of annual totals (Fig. 10); the exception is in southeastern Tibet where extreme precipitation contributes less than 30% to the total precipitation. To reveal the relationship between changes in total precipitation from extreme and nonextreme events, we conducted logistic regression with the annual number of extreme precipitation events as predictor and the annual total precipitation from nonextreme events as the predictant. The results are shown in Fig. 11. Positive coefficients are found over most areas of the country, indicating that changes in the number of extremes and nonextreme precipitation events are in phase. This suggests that trends in total precipitation over these regions come from trends in both extreme and nonextremes of the same sign. But there are regions where negative regression coefficients are found. In southwest China, an increase in the frequency of extreme precipitation events is associated with a decrease in the total amount of precipitation fallen during nonextreme events.

6. Conclusions and discussion

Using a recently developed comprehensive daily precipitation dataset for China, we have analyzed trends in both total and extreme precipitation over the past 50 years. In general, the number of rain days has decreased but the rainfall intensity has increased. Significant trends were found in different regions and seasons. However, trends cancel each other across the country, resulting in little change in total precipitation for the country as a whole. Western China experienced a significant increase in annual and seasonal total precipitation. Over eastern China, trends differ from south to north and from one season to another. Significant trends have been found in annual, winter, and summer precipitation, with downward trends in north China and upward trends in southern China including the Yangtze River. Such changes in precipitation have resulted in more frequent droughts in the north and more frequent and sometimes very severe floods in the south, especially in the mid–lower reaches of the Yangtze River. These changes of precipitation in eastern China may be associated with changes in the east Asian summer monsoon system. Extreme precipitation events have shown trend patterns similar to those of total precipitation. In regions of an increase in total precipitation extreme events have also increased, and vice versa. In many regions, such as western China, the lower and mid reaches of the Yangtze River, and north China, trends in extreme events and in total precipitation from nonextremes are generally in phase. The changes in the number of extreme precipitation events are the result of changes in both the number of rain days and the intensity. For a given intensity, the more rain days, the better chance for an extreme to occur. Similarly, higher intensity will result in more extremes if the total number of rain days in a year does not decrease. The decrease in the number of rain days and increase in the average rainfall intensity have impacted the occurrence of extreme precipitation. In southern China, the effect of enhanced intensity overwhelms that of reduced rain days, resulting in an increase in the number of extreme events. In northern China, the decrease in the number of rain days exerted stronger influence on the frequency of extremes than the increased rainfall intensity did, producing negative trends in the frequency there. Note that the negative trend in the frequency of precipitation days greater than its 95th percentile does not necessary mean that the precipitation extreme over this region is less intense. In fact, we computed a daily precipitation amount at the 95th percentile for every station and for each of the 50 years and found that this quantity has significantly increased in southern China, but experienced little change in northern China (not shown). That is, while extremes in southern China have increased, they are not less intense in northern China. The mechanism of precipitation change in China is an interesting topic to study in the future.

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APPENDIX

The Logistic Regression Model

Frei and Schar (2001) suggest the use of a binomial distribution to model the count n of events at a particular time (e.g., the number of heavy daily precipitation in a year). The probability for n events in m-independent trials (days) is given by

$$B(n; \pi, m) = \binom{m}{n} \pi^n (1 - \pi)^{m-n} \tag{A1}$$

with

$$\binom{m}{n} \equiv \frac{m!}{n!(m-n)!},$$

where π is the probability of the event occurrence. The expected value $\langle n \rangle$ and variance var(n) of the distribution are

$$\langle \eta \rangle = m\pi, \mathrm{var}(\eta) = m\pi(1 - \pi). \tag{A2}$$

The logistic regression model expresses a transformed form of the expected value of counts (or equivalently the event probability π) as a linear function of a covariate x:

$$\eta(\pi) = \alpha + \beta x. \tag{A3}$$

In the case of the trend model, x is replaced by time t (the year of the period), and it is the total precipitation amount when we regress the number of extreme events on the total precipitation. Here α and β are the regression intercept and coefficient, respectively, to be estimated from the data: η is a prescribed link function that transfers the value range of π Î [0, 1] onto the real axis. We have used the canonical link of the logistic regression model:

$$\eta(x) = \mathrm{log}it(x) \equiv \log\left(\frac{x}{1 - x}\right). \tag{A4}$$

As a result, the connection between the expected value of events and the covariate takes the form:

$$\pi(x: a, \beta) = \exp(a + \beta x)/[1 + \exp(a + \beta x)]. \tag{A5}$$

The parameters α and β of logistic regression model are estimated using an S-plus implementation of the maximum likelihood method (Venables and Ripley 1997). The statistical significance of the fitted model is tested against the null hypothesis (β= 0), using the deviance difference between the fitted model and null hypothesis as the test statistic (McCullagh and Nelder 1989). Test results are given for a two-tailed test with a significance level of 5%.

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