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ORIGINAL PAPER

Detection of trends in precipitation extremes in Zhejiang, east China

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Abstract Extreme weather exerts a huge impact on human beings and it is of vital importance to study the regular pattern of meteorological and hydrological factors. In this paper, a selection of seven extreme indices is used to analyze the trend of precipitation extremes of 18 meteorological stations located in Zhejiang Province, east China using the Mann–Kendall test. Then the precipitation trends in the plum season (from May to July) and typhoon season (from August to October) are studied separately. The results show that the precipitation trend varies from east to west. There is a positive trend in the east and a negative one in the west. The largest part of Zhejiang Province shows a positive trend in heavy precipitation and the most significant upward trend is detected in Dinghai with 3.4 mm/year for precipitation on very wet days. Although the upward trend of extreme precipitation is not prevailing, the range of increase in specific areas is apparent, like Dinghai with 1.3 mm/year. Precipitation intensity exhibits an upward trend in most areas and a typical upward trend can be found in Dachendao, Tianmushan, and Yuhuan with 0.04, 0.02, and 0.05 mm/year respectively. Precipitation intensity in both plum and typhoon seasons has increased too, especially for the coastal stations.

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1 Introduction

The analysis of trends in extreme hydrological events is very important for water management under rapid environmental change. 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). Chen et al. (2006) reported that the impact of global climate change, mainly increasing global temperature and altering precipitation patterns on regional hydrological cycles especially in arid regions is noticeable. With significant global warming, some extreme events will become more and more frequent and much effort has been made to detect and analyze the trend of the occurrence of extreme events which happened in the past decades.

Quite a lot of studies have shown that the changes in precipitation-related indices around the globe exhibited strong local to regional-scale variability. Tebaldi et al. (2007) found a significant downward trend in dry days which describe a tendency towards less extended dry periods, and in lower latitudes of the northern hemisphere it rains less frequently but precipitation intensity has increased. In some part of Europe, like the Carpathian Basin, regional intensity and frequency of extreme precipitation have increased (Bartholy and Pongracz 2007). In Northern Eurasia, there are seasonal differences in the precipitation trend, and trends for summer precipitation intensity in twenty-first century are positive but less significant than those for winter trends (Khon et al. 2007). Moberg et al. (2006) also obtained a similar conclusion by studying precipitation extremes in Europe for the period 1901–2000. They found an average increase of winter precipitation, but did not find any disproportionately large increase of heavy precipitation events in winter. Rather, the trends in extreme precipitation totals in winter change roughly in proportion to the trend in seasonal precipitation totals. While in summer, there is a tendency for significant positive trends for regions north of 40° N in Europe. Goubanova and Li (2007) found that precipitation extremes increase in all seasons except in summer around the Mediterranean basin using three global climate models in which precipitation extreme is defined as 24-h maximum precipitation. Some studies have shown that heavy precipitation frequencies in the U.S.A. were at a minimum in the 1920s and 1930s, and increased to the 1990s (Groisman et al. 2004; Kunkel et al. 2003). While in Canada during the period between 1950 and 2003, there were more days with precipitation but a decrease in daily intensity and no consistent changes were found in extreme precipitation (Vincent and Mekis 2006).

In China, much work has been done on the effect of climate change on precipitation. Zhai et al. (1999) reported that for China as a whole, there were no significant trends in much greater than normal amounts of annual precipitation, but there was a significant increase in the trend related to the proportion of China affected by extremely high rainfall intensities. At the end of 1970s and the beginning of 1980s, there is an abrupt change of the number of days with extreme precipitation and the percentage of extreme precipitation over China (Zhang et al. 2008). Because of the large size of China, the situation varies. In the middle and western parts of Guizhou province (south China), enhanced precipitation extremes, which were mainly reflected by a decreasing number of rainy days and an increasing precipitation intensity, were detected after the early 1990s (Zhang et al. 2010b). However, Tarim River Basin (northwest China), an area with an extreme arid climate, has experienced an increase of 23% in precipitation after 1986 (Chen et al. 2006). In some northern areas in China, like the Loess Plateau, temporal changes of precipitation-based indicators showed a mixed pattern of upward and downward trends but no significant trend was detected for extreme precipitation (the extreme precipitation threshold is the 90th percentile of rainy amounts; Li et al. 2010). While in the north-western Yangtze basin, significant negative trends were found for extreme precipitation (Su et al. 2008). In their study, extreme precipitation is defined as the daily precipitation exceeding the mean 95th percentile in the entire observational period (1960–2004).

The key objectives of this work are to detect the trends of extreme precipitation in Zhejiang Province, east China from the 1950s to the 2000s using a selection of seven extreme indices, and to detect the trends of precipitation in the plum season and typhoon season through applying the Mann–Kendall test.

2 Study area and data

Zhejiang Province (118° E–123° E, 27° N–31° N), with an area of 10.18×10^4 km^2, is located in the southeast of China (Fig. 1). The province is dominated by a subtropical monsoon climate, which is characterized by abundant precipitation and high temperatures in summer and rainless and cold winters. The annual mean temperature is 15−18°C. The average annual precipitation varies between 980 and 2,000 mm. These large differences in precipitation are due to geographical differences. Almost every year, coastal areas suffer from extremely heavy precipitation caused by typhoons. However, the impact of typhoons on inland areas is much less. In Zhejiang Province, there are eight major river systems and the largest one is the Qiantang River Basin. The Qiantang River is originated from Anhui Province, flowing eastward to the East China Sea. The river has a length of 410 km and a drainage area of 4.2×10^4 km^2.

The main precipitation occurs in the plum season (from May to July) and typhoon season (from August to October). In the plum season, the southeast wind from the Pacific Ocean takes warm, humid air to the inland, when warm air and cold air converge, and precipitation forms. In the typhoon season, typhoons with heavy rainstorm occur almost every year. In 2004, the highest wind speed of typhoon Rananim reached 45 m/s. In 2005, the highest wind speed of typhoons Masta and Khanun reached 45 and 50 m/s respectively. In 2006, the highest wind speed of typhoon Saomai was 60 m/s, and typhoon Morakot 40 m/s in 2009. All these typhoons have caused severe flooding problems. Zhejiang Province plays an important role in the socio-economic development in China. However, frequent floods have affected the local economic, environmental, and ecological development.

In this study, daily precipitation data from 18 meteorological stations are used. Figure 1 shows the locations of these 18 stations. The descriptions of the 18 meteorological stations are given in Table 1. These data have been provided by the National Climate Center of the China Meteorological Administration. Daily precipitation data are available from 42 to 58 years.

The precipitation series are selected on the basis of the series length and data completeness. Because extreme analyses are critically dependent on the serial completeness of data, many station series with several years missing or more than four missing observations per year are rejected. The selected series have also been quality controlled for inhomogeneity (Wang 2003). The results revealed that there is no breaking point and all the precipitation series used in the study were consistent. The main purpose of the quality control procedure is to identify errors usually caused by data processing such as manual keying. Here outliers are defined as the mean value of the year plus or minus four times the standard deviation of the value for that calendar day in this

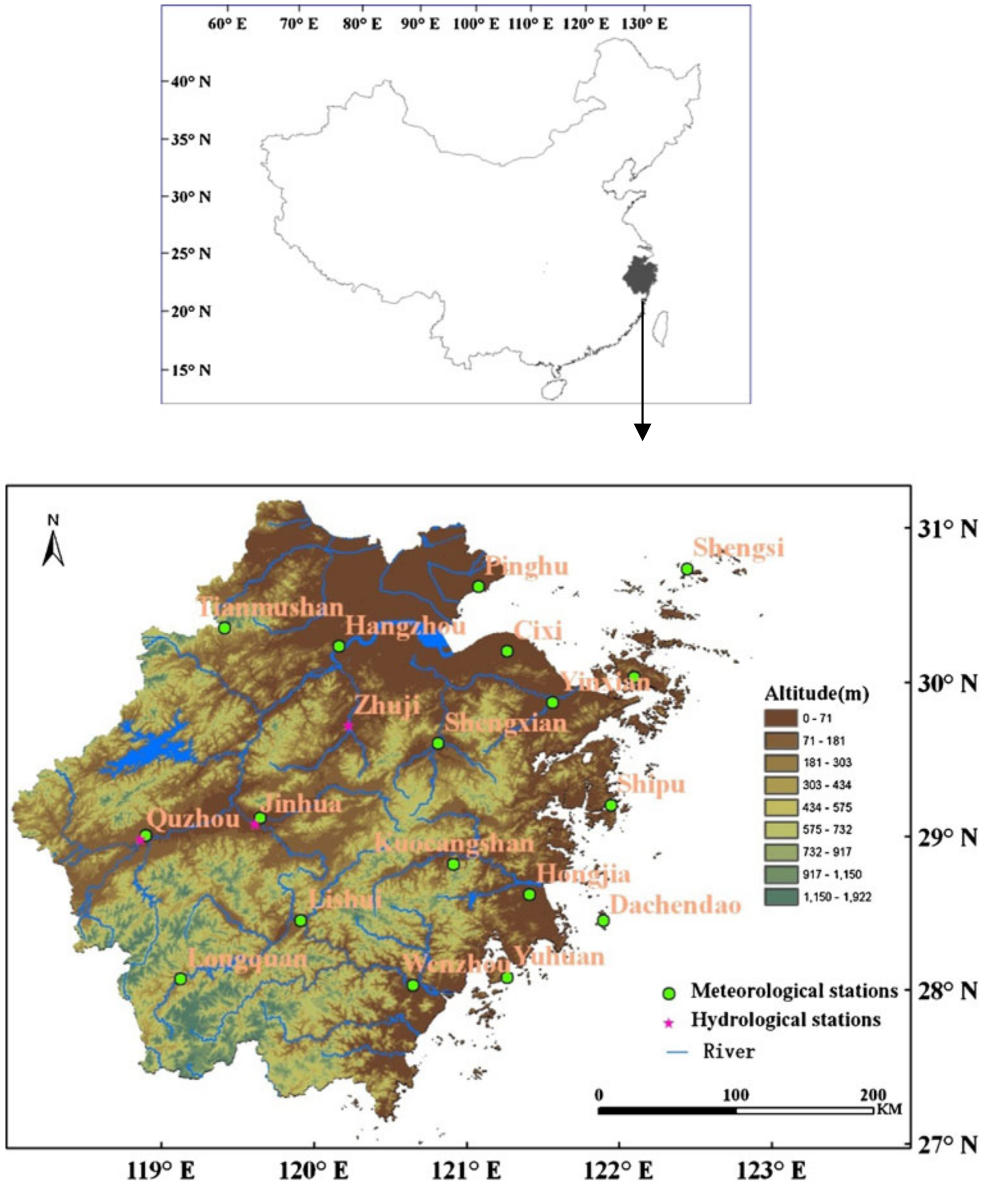

Fig. 1 The location of Zhejiang Province in China and the distribution of meteorological and hydrological stations

entire series. If the values are outside the thresholds, they are marked as potentially erroneous. The potentially erroneous values are checked and set to missing values.

The selected stations have not been moved from the original site location. Because the changes in station location often lead to spurious jumps and/or gradual shifts, the inhomogeneity may severely affect the extremes.

3 Methodology

3.1 Mann–Kendall test

In this study, the Mann–Kendall statistical test (MK) (Mann 1945), a non-parametric approach, is applied to determine whether long-term temporal trends exist for the seven indices selected for each of the 18 meteorological stations. The Mann–Kendall test is a rank-based procedure, which is less sensitive to outliers than parametric approaches and it is widely used in hydrology and climatology (Burn 2008; Chen et al. 2007; Zhang et al. 2010a).

In the MK test, the test statistic is calculated as:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k) \quad (1)$$

Where

$$\operatorname{sgn}(x_j - x_k) = \begin{cases} 1 & \text{if } x_j - x_k > 0 \\ 0 & \text{if } x_j - x_k = 0 \\ -1 & \text{if } x_j - x_k < 0, \end{cases}$$

x_j and x_k are the sequential data values, n is the length of the

Table 1 Detailed meteorological records of stations in Zhejiang

Name	Period	Length (years)
Hangzhou	1951–2008	58
Jinhua	1953–2008	56
Shengxian	1953–2008	56
Tianmushan	1956–1997	42
Quzhou	1951–2008	58
Cixi	1954–2008	55
Shengsi	1959–2008	50
Dinghai	1955–2008	54
Yinxian	1953–2008	56
Lishui	1953–2008	56
Longquan	1953–2008	56
Kuocangshan	1956–1993	48
Wenzhou	1951–2008	58
Hongjia	1951–2008	58
Dachendao	1958–2008	51
Yuhuan	1957–2008	52
Shipu	1956–2008	53
Pinghu	1954–2008	55

data series, and the normally distributed variate z is computed as:

$$z = \begin{cases} \dfrac{S-1}{\mathrm{Var}(S)} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \dfrac{S+1}{\mathrm{Var}(S)} & \text{if } S < 0 \end{cases} \tag{2}$$

where

$$\mathrm{Var}(S) = \frac{n(n-1)(2n+5) - \sum_t t(t-1)(2t+5)}{18}$$

Var (S) is the variance of the test statistic S (see e.g. Hamed 2009) and t is the extent of any given tie. A tie is the sample data having the same value and the summation is over all ties (Hirsch et al. 1982). The null hypothesis is that a series $x_1,\ldots,x_n$ is independent and identically distributed. At the 95% confidence level, if $|z|>1.96$, the null hypothesis of no trend is rejected.

In the Mann–Kendall test, another useful index is the Kendall slope, which is the magnitude of the monotonic trend and is given as

$$\beta = \mathrm{Median}\left(\frac{x_i - x_j}{i - j}\right), \forall j < i \tag{3}$$

in which $1<j<i<n$: The estimator β is the median over all combinations of record pairs for the whole data set.

3.2 Extreme precipitation indices

Different research groups may define different extreme indices for their particular purpose (Booij 2002; Chu et al. 2010; Lizuma et al. 2010; Qian et al. 2010; Rodrigo 2010; Szwed et al. 2010; Vincent and Mekis 2006). The Expert Team on Climate Change Detection and Indices (ETCCDI) has been jointly established by the WMO Commission for Climatology and the Research Programme on Climate Variability and Predictability (CLIVAR). The ETCCDI defined 27 core extreme indices based on daily temperature and precipitation amount. Exact definitions of all the indices are available from the ETCCDI website (http://cccma.seos.uvic.ca/ETCCDI).

In this study, however, only extreme indices derived from daily precipitation are considered. Altogether, seven extreme indices are chosen from the 27 climate indices and are listed in Table 2. An R-based program, RClimDexV3 developed at the Climate Research Branch of the Meteorological Service of Canada and available from the ETCCDI Web site (http://cccma.seos.uvic.ca/ETCCDMI), is applied to calculate these seven extreme indices for the selected 18 meteorological stations.

4 Results and discussion

4.1 Trends of seven extreme precipitation indices

Seven extreme indices are calculated for the 18 meteorological stations in Zhejiang Province and the Mann–Kendall test is used to test any trend in these indices. The magnitude of the trend is described by estimator β given in Eq. 3 and the significance level is 0.05. The results are shown in Fig. 2a–g.

Table 2 Definitions of the indices of precipitation

Indices	Description
SDII	Simple daily intensity index, average daily precipitation amount on wet days with RR≥1 mm. Let RR be the daily precipitation amount on a wet day
Rx5day	Annual maximum consecutive 5-day precipitation
CDD	Maximum length of dry spell, maximum number of consecutive days with RR<1 mm
CWD	Maximum length of wet spell, maximum number of consecutive days with RR≥1 mm
PRCPTOT	Annual total precipitation in wet days: with RR≥1 mm
R95pTOT	Annual total precipitation when RR>95th percentile of precipitation on wet days during the study time series (precipitation fraction due to very wet days)
R99pTOT	Annual total precipitation when RR>99th percentile of precipitation on wet days during the study time series (precipitation fraction due to extremely wet days)

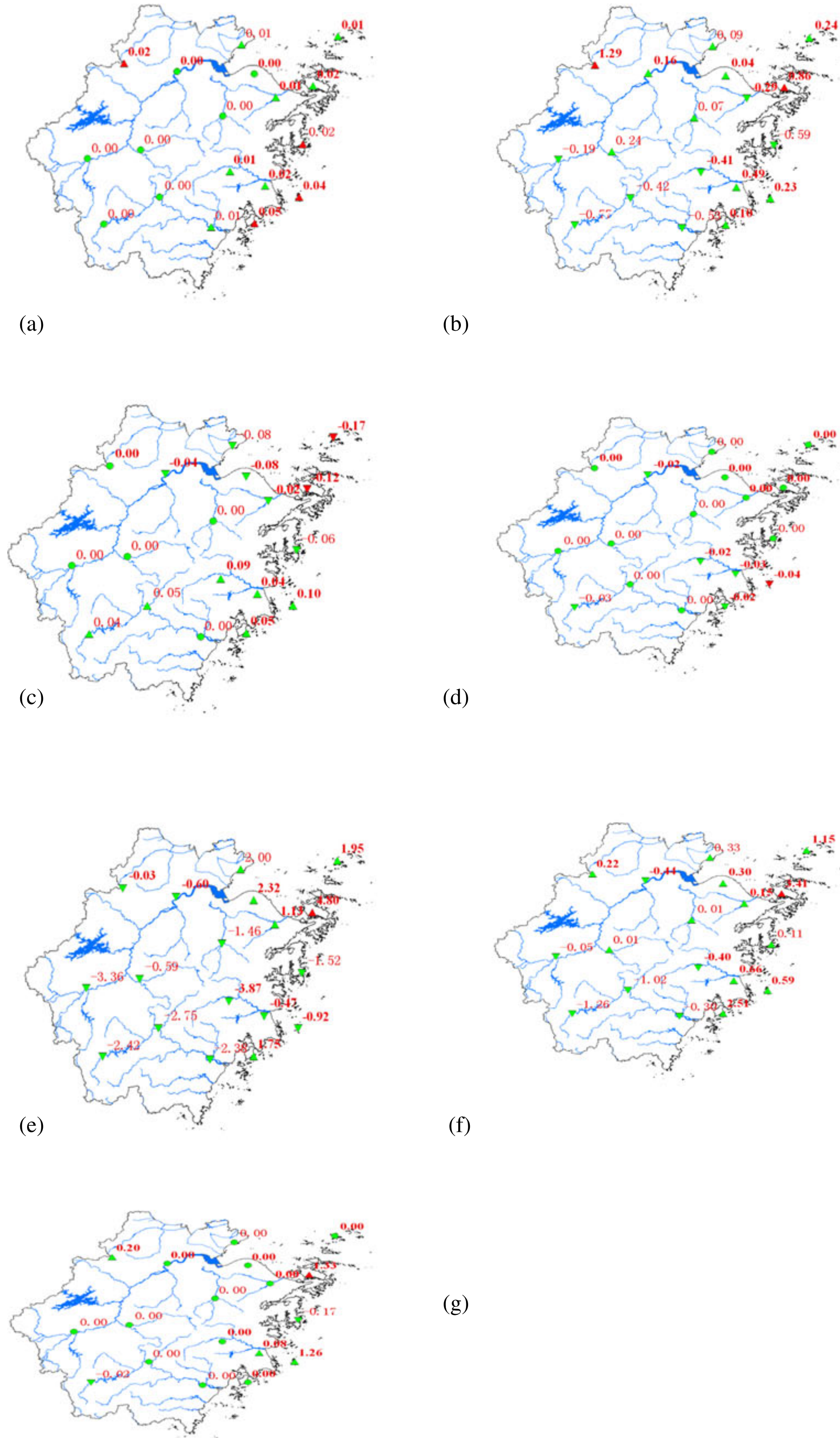

Fig. 2 Spatial distribution of trends in seven precipitation indices (Here, *circle* in *green* represents no trend, *up-pointing triangle* and *down-pointing triangle* in *green* color represent positive and negative trends, respectively, *up-pointing triangle* and *down-pointing triangle* in *red* color represent significant trends at the 0.05 confidence level). **a** Simple daily intensity index (SDII, millimeters per year), **b** maximum 5-day precipitation (Rx5day, millimeters per year), **c** consecutive dry days (CDD, days per year), **d** consecutive wet days (CWD, days per year), **e** annual wet days precipitation (PRCPTOT), **f** annual total precipitation amount when RR>95th percentile (R95pTOT, millimeters), **g** annual total precipitation amount when RR>99th percentile (R99pTOT, millimeters)

Figure 2a shows the trend of the simple daily intensity index (SDII) for the 18 meteorological stations. Among the 18 stations, 11 stations are characterized by positive trends, and significant positive trends are observed in Yuhuan (0.05 mm per year), Dachendao (0.04 mm per year), Tianmushan (0.02 mm per year) and Shipu (0.02 mm per year). The strongest positive trend is detected in Yuhuan with 0.05 mm per year from 1957 to 2008. From Fig. 2a, it can be observed that there is a particular spatial distribution of the SDII index. The eastern part of Zhejiang Province has experienced an increased daily precipitation amount on wet days, while the inland area has not experienced such a change. The precipitation intensity of all the coastal areas, including Pinghu, Shengsi, Yinxian, Dinghai, Shipu, Hongjia, Dachendao, Yuhuan, and Wenzhou Stations, are dominated by positive trends with the exception of Cixi. The other seven stations show weak negative trends or even no trend, of which most stations are located in the central and southwestern parts of Zhejiang Province.

The trends of maximum 5-day precipitation (Rx5DAY) are shown in Fig. 2b. Among the 18 stations, 11 stations show increasing trends, most of which are located in the north or coastal areas of the province. The increasing trends in Tianmushan (north) and Dinghai (north) are statistically significant at the 0.05 significance level. The highest positive trend is found in Tianmushan Station with 1.3 mm per year and the highest value for the Rx5DAY index is also found in Tianmushan with 603.7 mm in 1963. Dinghai has an upward trend of 0.86 mm per year. The other seven stations show negative trends and are mainly located in a vast area in the south or inland part of Zhejiang Province like Longquan with a trend of −0.77 mm per year and Lishui with −0.42 mm per year. It is noted that in Shipu although the SDII index has a significant upward trend with 0.02 mm per year, Rx5DAY for this station exhibits an opposite trend with −0.59 mm per year, which implies that the daily precipitation intensity increased but it had a more uniform temporal distribution.

The trends of the maximum number of consecutive dry days (CDD) are shown in Fig. 2c, varying from north to south and from inland to coastal areas. Seven stations with negative trends are located in the northern region of Zhejiang Province (mainly coastal). Six stations in the southern region were dominated by a positive trend. Inland stations did not show any trend. Significant negative trends for CDD are detected in Dinghai with −1.2 days per decade from 1955 to 2008, and Shengsi with −1.7 days per decade from 1959 to 2008. The decrease of the CDD index in Dinghai is related to the increased extreme precipitation and such an increase is reflected in indices like R95pTOT and R99pTOT described later in this section while in Shengsi there is a different cause for the dropped CDD indices. The average maximum number of the CDD of Shengsi is about 32 days from 1959 to 2008 and in recent 10 years the average value has dropped to 24 days. The extreme precipitation of Shengsi does not show any change. It is the rising total precipitation that contributed to the dropped CDD indices (See Fig. 2e, annual wet days precipitation (PRCPTOT)).

Figure 2d shows the trends of consecutive wet days (CWD). A small area in the southeast part of Zhejiang Province exhibits a decreasing trend, while the majority of the area (12 stations) does not show any trend. The mean value of CWD for Zhejiang Province is 11 days from 1951 to 2008, and the highest number was recorded in Kuocangshan with 24 days in 1958. The strongest negative trends are detected in Dachendao with −0.43 days per decade (significant). It is found that after 2003, all the stations have not exceeded 11 days for this index, and the average number in Zhejiang Province dropped to only 6 days, indicating that the weather is getting drier in the southeast in recent years because of the drop in CWD and the increase in CDD. The situation is particularly serious in Dachendao for which the average CDD is 29 days and the average CWD is 6 days from 1958 to 2008. However, the CDD index is increasing at the speed of 1 day per decade while the CWD index is decreasing at 0.4 days per decade.

Figure 2e shows the trends of PRCPTOT. The trends of annual wet days precipitation in most stations are not statistically significant at the 0.05 significance level. Most stations (12 out of 18 stations) are dominated by negative trends. Moreover, coastal stations in the northeast of Zhejiang Province which are higher in average precipitation are dominated by positive trends, and significant positive trends are detected in Dinghai with 4.8 mm per year. Meanwhile, it is found that the amount of precipitation in the plum season and typhoon season accounts for over 63% of the total annual wet days precipitation. Therefore, the trends of precipitation in these two seasons will be discussed later separately.

The trends of the precipitation amount on very wet days are shown in Fig. 2f. Here, we define the days with precipitation that exceeds the 95 percentile of the precipitation as very wet days. Stations including Tianmushan, Shipu, Hongjia, and Yuhuan have experienced 1 year without any very wet days, and all other stations have experienced very wet days in each year. The highest precipitation at very wet days was recorded in Kocangshan in 1990 with 1,757 mm. It is found that four out of five stations with more than 1,000-mm precipitation are located in the southeast area. Twelve out of 18 stations are dominated by positive trends for this index. All the coastal stations except Wenzhou are dominated by positive trends. The strongest and the only significant positive trends for R95pTOT are found in Dinghai (coastal). While negative trends are prevailing in the inland areas, Longquan, an inland station, has experienced stronger negative trends than any other stations in this study. The number of very wet days has increased in most parts of Zhejiang province. This result is similar to that of the IPCC Fourth Assessment Report which indicates the increase in the proportion of total precipitation from heavy rainfall over most areas. This upward trend is obvious along the coastal area where there is a higher amount of precipitation originally. While in the inland area, where the precipitation amount is less than that of coastal area, this indicator decreased. It means that the spatial distribution of precipitation is becoming more non-uniform.

Figure 2g shows the trends of the precipitation amount on extremely wet days (R99pTOT). We define the days with precipitation that exceeds the 99 percentile of the precipitation as extremely wet days. Although some parts of Zhejiang Province have experienced slightly positive or negative trends in extreme precipitation, there is no trend in most areas. However, a significant positive trend is detected in Dinghai with 1.3 mm per year. Every station in this study has experienced extremely wet days, and Shengxian has a record that in a period from 1987 to 2000 every year extremely wet days appeared. The highest value for this index differs from one station to another. For example, Hongjia has a record of 975 mm for the R99pTOT index in 2005, while in the same year it was only 80.8 mm for Shipu. The majority of the stations present no trends for precipitation in R99pTOT. Four stations, three along the coast and one in the mountain areas, present positive trends.

4.2 Precipitation trends in plum season and typhoon season

According to the analysis of the precipitation indices, a decline is found in total precipitation in most of the stations, but the value of the SDII indices is increasing in 12 out of 18 stations. In other words, the total precipitation amount presents an opposite trend to the precipitation intensity. Floods happen frequently in summer in the study area. It is noted that the precipitation amount from May to July accounts for about 70% of the total annual amount. The precipitation from May to October can be divided into two categories in terms of different formation mechanisms (see section 2). So it is important to look into the precipitation pattern for each specific season when the precipitation amount is high.

In this study, using the Mann–Kendall test, the precipitation trends are initially estimated for all the stations in the plum season and typhoon season respectively. The inverse distance weighting method (Shepard 1968) is then used here to interpret the spatial distribution of the trends of precipitation in plum season and typhoon season, and also the trend of the number of precipitation days. Inverse distance weighting is a process of assigning values to unknown points by using values from usually a scattered set of known points. The value at the unknown point is a weighted sum of the values of the known points. If different trends are observed for precipitation amounts and precipitation days, this would reflect changes in the characteristics of precipitation. For instance, a positive trend in precipitation and no trend in the number of precipitation days would mean that the precipitation has become more intense. A zero trend in precipitation amount and a positive trend in the number of precipitation days would instead mean that precipitation falls more often but less intense. So compared to the trend of precipitation, if there is a strong contrast in the precipitation trend and the trend in the number of precipitation days, it means there is a change in precipitation intensity. The results for the plum season are shown in Figs. 3 and 4 and the results for the typhoon season are shown in Figs. 5 and 6. The value represents the degree of change of precipitation trend.

For the plum season, the strongest precipitation trends are found in the northwest and southwest inland region. The northwest inland areas show a positive trend and the strongest upward trend is 4.3 mm per year detected in Tianmushan from 1956 to 1997. But large areas in the southwest part witness a decline in the plum season precipitation and the strongest negative trend is found in Lishui with −2.4 mm per year from 1953 to 2008. There is not an obvious trend of precipitation for regions in the central and northeast areas. The east coastal areas, including Hongjia and Yuhuan, show a negative trend. For the number of precipitation days, there is a significant decrease in Lishui and Dachendao with −0.1 day per year and −0.2 day per year respectively. Ten stations show a negative trend and seven show no trend. Only in Tianmushan, it rains more often. By comparing Figs. 3 and 4, it can be seen that the spatial distribution of trend in precipitation amount and the number of precipitation days is very similar. But the change in the precipitation intensity can be observed in the western part of Zhejiang Province. Stations such as Jinhua, Cixi, Pinghu, Shengsi, Dinghai, Yinxian,

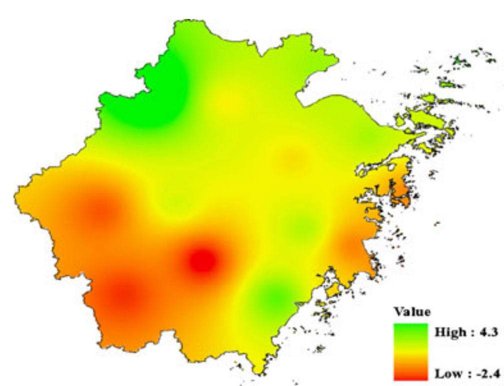

Fig. 3 Precipitation trend in plum season

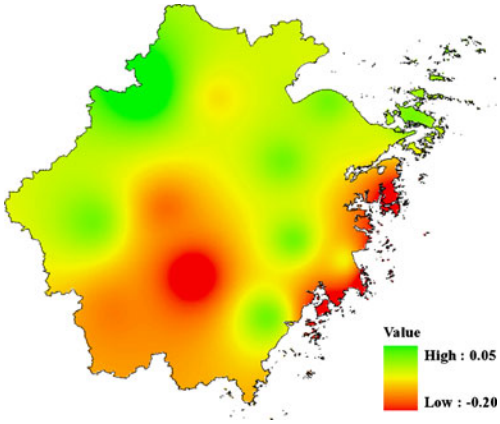

Fig. 4 Trend of the number of precipitation days in plum season

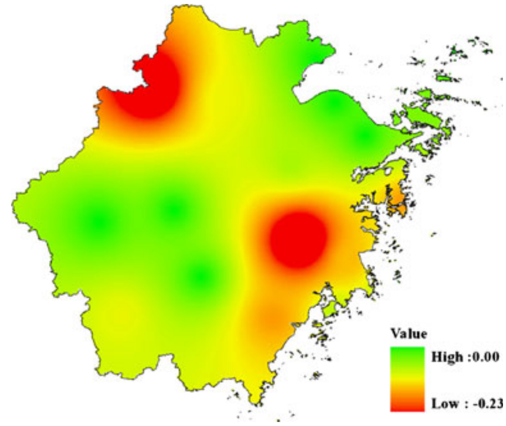

Fig. 6 Trend of number of precipitation days in typhoon season

Kuocangshan, and Wenzhou share the same precipitation pattern. Although the number of precipitation days may decrease or does not change, the intensity of the precipitation has become stronger in the plum season because of the increase in precipitation amount.

In the typhoon season, it is noted that there is a great difference in the precipitation trend and trend of the number of precipitation days when compared to those of the plum season. Figures 5 and 6 show that the trend of precipitation presents a geographical distribution feature in East Zhejiang Province. Negative trends gradually change into positive trends from the west inland area to the east coastal area. Eleven stations show negative trends with the strongest ones in Tianmushan and Hangzhou. Nine out of the 11 stations are located in the inland area. The strongest upward trend in precipitation is 3.6 mm per year in Dinghai from 1955 to 2008. Such a strong increase is reflected in the increase of extreme precipitation indicators like R95pTOT and R99pTOT. The major cause of the increase in precipitation is that in the typhoon season more precipitation has been brought to this area during the period from 1955 to 2008. The most significant downward trend is −2.1 mm per year in Hangzhou from 1951 to 2008. Tianmushan has experienced a high decrease of −7.1 mm per year but it is not significant because Tianmushan is in the mountain area and the total amount of precipitation is much higher than other areas. It is noticed that during the typhoon season, the number of precipitation days does not show any trend in most parts. Only in the northwestern and southeastern parts of Zhejiang Province, the number of precipitation days in the typhoon season decreases. Nevertheless, in places like Pinghu, Cixi, Dinghai, Hongjia, Dachendao, and Yuhuan, the precipitation has become more intense because of the increasing precipitation amount and decreasing or unchanged number of precipitation days.

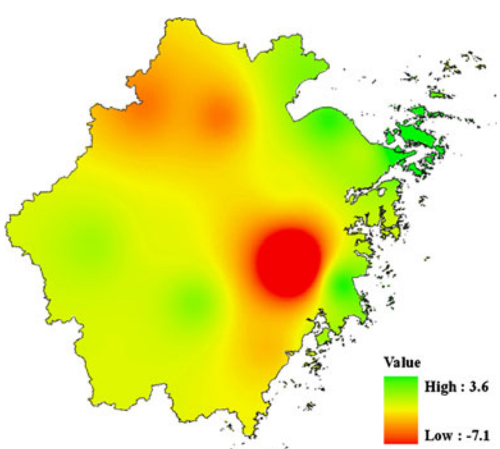

Fig. 5 Precipitation trend in typhoon season

5 Conclusions

In this paper, the trends of precipitation extremes have been investigated for Zhejiang Province, China. It is found that 11 out of 18 stations in Zhejiang Province have experienced a positive trend for SDII indices, most of which are located in the east coastal area. Significant upward trends were detected in Yuhuan (0.05 mm per year), Dachendao (0.04 mm per year), Tianmushan (0.02 mm per year) and Shipu (0.02 mm per year). Also, 11 stations showed positive trend for Rx5DAY indices, and significant positive trends were found in Tianmushan and Dinghai. There was a negative trend for the Annual Wet Day Precipitation, and the negative trend is especially common in the west inland areas where there is a lower mean value for precipitation. But the coastal areas in the northeast showed a positive trend with the strongest in Dinghai with 4.8 mm per year. This result corresponds well with the historical record that drought happened more frequently in the western part of Zhejiang Province than the eastern part, and the downward trend in the west and upward trend in the east has made the situation even worse (Wen et al. 2006). This is because the eastern part is deeply affected by a maritime climate which brings much precipitation in summer, while the maritime climate does not have a strong influence on the western inland areas as it has in the eastern parts.

Decreased numbers of consecutive dry days were observed in northern areas. Dinghai and Shengsi, both in the northeast part, have witnessed a significant decrease, −1.2 and −1.7 mm per year respectively, while southern areas were dominated by a positive trend. For consecutive wet days, most area did not show any changes. Only in the southwestern part, a decreasing trend prevailed. But the most significant downward trend was in Dachendao with −0.43 days per decade in the eastern part. There was a decline in total precipitation amount in most areas, but in the northern coastal areas, there were upward trends and the most significant trend was found in Dinghai with 4.8 mm per year. Such a significant trend has been caused by the increasing precipitation amounts in the typhoon season. R99pTOT did not change for most parts of Zhejiang, but 12 out of 18 stations exhibited positive trends for precipitation in R95pTOT. Significant upward trends were detected in Dinghai with 3.4 mm per year, followed by Yuhuan with an increase of 2.5 mm per year (not significant). Other areas also showed upward trends in R95pTOT but not significant. It implies that climate change has exerted an impact on the precipitation of Zhejiang Province, which is reflected in an increase in heavy precipitation, a decrease in numbers of consecutive dry days and a more non-uniform spatial distribution of precipitation which causes a more unbalanced situation.

Also, precipitation in the plum season and typhoon season was studied separately. The results showed that the precipitation trend pattern in the typhoon season, with an increase in the coastal area and a decrease in the inland area, is very similar to the trend of R95pTOT. It indicates that the increasing precipitation in the typhoon season is the main cause of the positive trend for precipitation. For example, the most representative station was Dinghai where significant positive trends were detected for R95pTOT (3.4 mm per year), R99pTOT (1.3 mm per year), and precipitation in the typhoon season (3.6 mm per year), but the positive trend was very weak for the plum season. The upward trend in the extreme indices showed that the eastern part is experiencing more extreme weather in summer, which is most likely to be caused by typhoons. Besides, precipitation intensity in both plum season and typhoon season increased. It is reflected in the increasing precipitation amount and decreasing number of precipitation days in those two seasons.

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References

Bartholy J, Pongracz R (2007) Regional analysis of extreme temperature and precipitation indices for the Carpathian Basin from 1946 to 2001. Global Planet Change 57(1–2):83–95

Blender R, Fraedrich K (2006) Long-term memory of the hydrological cycle and river streamflows in China in a high-resolution climate model. Int J Climatol 26(12):1547–1565. doi:10.1002/Joc.1325

Booij MJ (2002) Extreme daily precipitation in Western Europe with climate change at appropriate spatial scales. Int J Climatol 22:69–85. doi:10.1002/joc.715

Chen YN, Takeuchi K, Xu CC, Chen YP, Xu ZX (2006) Regional climate change and its effects on river streamflow in the Tarim Basin, China. Hydrol Process 20(10):2207–2216. doi:10.1002/Hyp.6200

Chen H, Guo SL, Xu CY, Singh VP (2007) Historical temporal trends of hydro-climatic variables and streamflow response to climate variability and their relevance in water resource management in the Hanjiang basin. J Hydrol 344(3–4):171–184. doi:10.1016/j.jhydrol.2007.06.034

Chu PS, Chen YR, Schroeder TA (2010) Changes in precipitation extremes in the Hawaiian Islands in a warming climate. J Climate 23(18):4881–4900. doi:10.1175/2010jcli3484.1

Goubanova K, Li L (2007) Extremes in temperature and precipitation around the Mediterranean basin in an ensemble of future climate scenario simulations. Global Planet Change 57:27–42

Groisman PY, Knight RW, Karl TR, Easterling DR, Sun BM, Lawrimore JH (2004) Contemporary changes of the hydrological cycle over the contiguous United States: trends derived from in situ observations. J Hydrometeorol 5(1):64–85

Hamed KH (2009) Exact distribution of the Mann–Kendall trend test statistic for persistent data. J Hydrol 365:86–94

Hirsch RM, Slack JR, Smith RA (1982) Techniques of trend analysis for monthly water-quality data. Water Resour Res 18(1):107–121

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

Khon VC, Mokhov II, Roeckner E, Semenov VA (2007) Regional changes of precipitation characteristics in Northern Eurasia from simulations with global climate model. Global Planet Change 57 (1–2):118–123

Kunkel KE, Easterling DR, Redmond K et al (2003) Temporal variations of extreme precipitation events in the United States: 1895–2000. Geophys Res Lett. doi:10.1029/2003gl018052, Vol. 30, Issue 17, Artcile ID 1900

Li Z, Zheng FL, Liu WZ, Flanagan DC (2010) Spatial distribution and temporal trends of extreme temperature and precipitation events on the Loess Plateau of China during 1961–2007. Quatern Int 226(1–2):92–100. doi:10.1016/j.quaint2010.03.003

Lizuma L, Briede A, Klavins M (2010) Long-term changes of precipitation in Latvia. Hydrol Res 41(3–4):241–252. doi:10.2166/Nh.2010.120

Mann HB (1945) Nonparametric tests against trend. Econometrica 13 (3):245–259

Moberg A, Jones PD, Lister D et al (2006) Indices for daily temperature and precipitation extremes in Europe analyzed for the period 1901–2000. J Geophys Res-Atmos 111:1–25. doi:10.1029/2006dj007103, Article ID D22106

Qian BD, Zhang XB, Chen K, Feng Y, O'Brien T (2010) Observed long-term trends for agroclimatic conditions in Canada. J Appl Meteorol Clim 49(4):604–618. doi:10.1175/2009jamc2275.1

Rodrigo FS (2010) Changes in the probability of extreme daily precipitation observed from 1951 to 2002 in the Iberian Peninsula. Int J Climatol 30(10):1512–1525. doi:10.1002/Joc.1987

Shepard D (1968) A two-dimensional interpolation function for irregularly-spaced data. In: Proceedings of the 1968 ACM National Conference. pp. 517–524. doi:10.1145/800186.810616

Su B, Gemmer M, Jiang T (2008) Spatial and temporal variation of extreme precipitation over the Yangtze River Basin. Quatern Int 186:22–31. doi:10.1016/j.quaint.2007.09.001

Szwed M, Karg G, Pinskwar I, Radziejewski M, Graczyk D, Kedziora A, Kundzewicz ZW (2010) Climate change and its effect on agriculture, water resources and human health sectors in Poland. Nat Hazard Earth Sys 10(8):1725–1737. doi:10.5194/nhess-10-1725-2010

Tebaldi C, Hayhoe K, Arblaster JM, Meehl GA (2007) Going to the extremes - An intercomparison of model-simulated historical and future changes in extreme events (vol 79, pg 185, 2006). Clim Chang 82(1–2):233–234

Vincent LA, Mekis E (2006) Changes in daily and extreme temperature and precipitation indices for Canada over the twentieth century. Atmos Ocean 44(2):177–193

Wang XL (2003) Comments on “Detection of undocumented change-points: a revision of the two-phase regression model”. J Climate 16(20):3383–3385

Wen KG, Xi GY, Xu WN (2006) China meteorological disaster. Zhejiang Meteorology Public Press, Zhejiang

Zhai PM, Sun AJ, Ren FM, Liu XN, Gao B, Zhang Q (1999) Changes of climate extremes in China. Clim Chang 42(1):203–218

Zhang DQ, Feng GL, Hu JG (2008) Trend of extreme precipitation events over China in last 40 years. Chinese Phys B 17(2):736–742

Zhang Q, Xu CY, Tao H, Jiang T, Chen YD (2010a) Climate changes and their impacts on water resources in the arid regions: a case study of the Tarim River basin, China. Stoch Env Res Risk A 24 (3):349–358. doi:10.1007/s00477-009-0324-0

Zhang Q, Xu CY, Zhang ZX, Chen X, Han ZQ (2010b) Precipitation extremes in a karst region: a case study in the Guizhou province, southwest China. Theor Appl Climatol 101(1–2):53–65