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Recent trends in observed temperature and precipitation extremes in the Yangtze River basin, China

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With 14 Figures

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Summary

The present study is an analysis of the observed extreme temperature and precipitation trends over Yangtze from 1960 to 2002 on the basis of the daily data from 108 meteorological stations. The intention is to identify whether or not the frequency or intensity of extreme events has increased with climate warming over Yangtze River basin in the last 40 years. Both the Mann-Kendall (MK) trend test and simple linear regression were utilized to detect monotonic trends in annual and seasonal extremes.

Trend tests reveal that the annual and seasonal mean maximum and minimum temperature trend is characterized by a positive trend and that the strongest trend is found in the winter mean minimum in the Yangtze. However, the observed significant trend on the upper Yangtze reaches is less than that found on the middle and lower Yangtze reaches and for the mean maximum is much less than that of the mean minimum. From the basin-wide point of view, significant increasing trends are observed in 1-day extreme temperature in summer and winter minimum, but there is no significant trend for 1-day maximum temperature. Moreover, the number of cold days $\leq 0\,^{\circ}$C and $\leq -10\,^{\circ}$C shows significant decrease, while the number of hot days (daily value $\geq 35\,^{\circ}$C) shows only a minor decrease. The upward trends found in the winter minimum temperature in both the mean and the extreme value provide evidence of the warming-up of winter and of the weakening of temperature extremes in the Yangtze in last few decades.

The monsoon climate implies that precipitation amount peaks in summer as does the occurrence of heavy rainfall events. While the trend test has revealed a significant trend in summer rainfall, no statistically significant change was observed in heavy rain intensity. The 1-day, 3-day and 7-day extremes show only a minor increase from a basin-wide point of view. However, a significant positive trend was found for the number of rainstorm days (daily rainfall ≥ 50 mm). The increase of rainstorm frequency, rather than intensity, on the middle and lower reaches contributes most to the positive trend in summer precipitation in the Yangtze.

1. Introduction

Weather hazards are amongst the most deadly and destructive natural disasters worldwide, and are caused mainly by extreme events rather than a variation of the mean climate (Plummer et al., 1999). Given the threat posed by global warming, the second assessment report (IPCC, 1995) raised the question: “Has the climate become more variable or extreme?” and since then, trends of climate extremes have received increasing attention from the public. Impacts of climate extremes are seen as an important realm for scientific research.

Although worldwide changes in extreme climate events have been detected in the past few decades, various studies have attempted to assess climate change-related extreme events at a

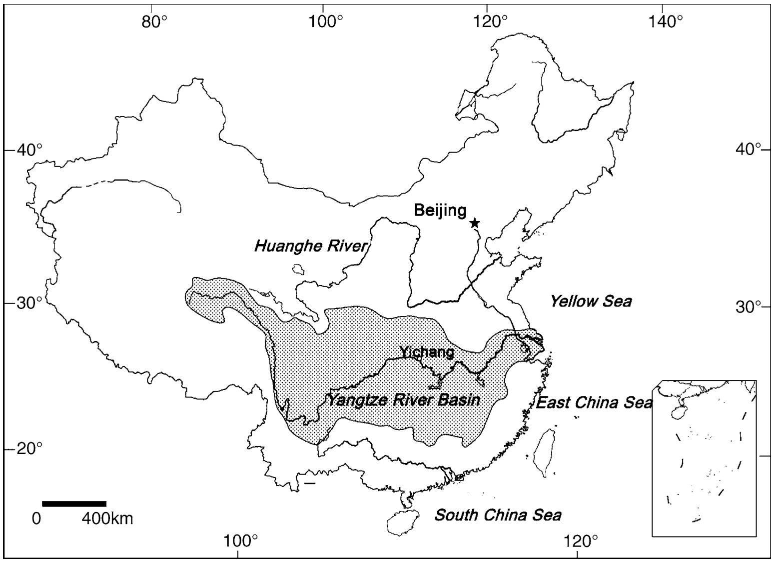

Fig. 1. Location of the Yangtze in China

regional level (IPCC, 2001). For the Northern Hemisphere, the downward trend in the number of extreme cold and hot days has been detected in the U.S. (De Gaetano, 1996; Karl et al., 1996), and in Central and Northern Europe, there is evidence of a decreasing number of cold days (Heino et al., 1999). The monthly or annual maximum temperature value has not revealed any obvious trends in the former Soviet Union and the U.S., but a significant increase was found in minimum temperature (Karl et al., 1991). The most recent studies on the trends of climate extremes in China have come to the same conclusion, that the frequency of cold extremes decreased during the second half of the 20th century (Frich et al., 2002; Zhai and Pan, 2003; Qian and Liu, 2004). The trend in extreme precipitation is more complicated than that of temperature. The number of days with heavy rainfall has increased in the U.S. (Karl et al., 1996) and Japan (Iwashima and Yamamoto, 1993), but a negative trend has been found in Northern China (Zhai and Pan, 2003). While heavy rain events in winter show a positive trend, heavy rain events in summer, however, have decreased in the United Kingdom (Osborn and Jones, 2000). The contribution of annual rainfall derived from extreme events has increased, but the frequency of extreme rainfall events has slightly decreased at the majority of selected stations in southeast Asia (Manton et al., 2001), while large amounts of high latitude rainfall in southeast Asia has been attributed to the duration and frequency, rather than to the intensity (Dairaku et al., 2004).

Covering an area of 1.8 million km^2, the Yangtze River (Fig. 1) is one of the longest rivers in the world and is well known for its disastrous floods in recent years. With the exception of some areas located in the Tibet plateau, most parts of the Yangtze are dominated by a sub-tropic monsoon climate characterized by four distinct seasons, spring (March, April, May), summer (June, July, August), autumn (September, October, November) and winter (December, January, February). Two types of monsoon current flow in a year, the Siberian northwest winter monsoon and the Asian southeast summer monsoon (or Indian southwest summer monsoon on the upper Yangtze reaches). The air temperature is very high during summer and is lower during winter. Precipitation is concentrated during the summer season and is closely related to a quasi stationary front (or mei-yu belt), which represents summer monsoon activity (Ho et al., 2003).

The Yangtze is extraordinarily vulnerable to climate warming due to its large seasonal and inter-annual variability of precipitation, dense population and the rapidly developed economy in China. Climate warming may affect the intensity or the probability of the occurrence of extreme weather events (Groisman et al., 1999). The present study is based on daily surface air temperature and precipitation data series from 1960 to 2002 observed at 108 meteorological stations. The main objective of this study is to identify whether or not the frequency or intensity of extreme climate events have increased during a climate warming period over the Yangtze River basin through the application of non-linear and linear trend analysis. The detailed analysis and understanding of trends of extreme climate events in the Yangtze are important to reduce the climate-induced flood risks and the impact of temperature extremes on society, agriculture, environment, and so on.

2. Data and methods

2.1 Data

The data sets collected here, provided by National Climate centre (NCC) of China Meteorological Administration (CMA), consist of daily maximum and minimum temperature data, and daily and monthly precipitation data from 168 stations distributed evenly all over the Yangtze River basin from Jan. 1, 1960 and Dec. 31, 2002.

Reliable data are the prerequisite to climate research. Missing data, the influence of urban heat islands, location or instrument changes at a station all bias the trend analysis (Portman, 1993; Karl et al., 1996; Zhai et al., 1999). Here, temperature data are found to be more complete than the precipitation data, since daily precipitation <0.1 mm, that falls in the form of frost, fog, and sleet are usually neglected. These immeasurable amounts of precipitation should not have much influence on present study. After rejecting stations close to the downtown area with population exceeding 0.5 million (for example, Shanghai station, Nanjing station etc) and those that have been relocated, homogeneity testing was performed at 108 stations (Fig. 2) in order to check the quality of the data.

Several strategies have been described in the literature, which have been developed to detect non-homogeneities in the data series (Peterson et al., 1998). In this paper, both the subjective double mass curve method and the objective student T test were applied to the annual mean temperature and annual precipitation time series of each station.

The double mass curve (Kohler, 1949) is a plot of the deviation from a station's accumulated values versus the average accumulation of the base group. Non-linearity or bends plots can be an indicator of changed conditions. In the Yangtze, regional averaged values, i.e. average annual mean temperature and annual precipitation time series of the upper Yangtze and the middle and lower Yangtze reaches respectively, might be defined as a reference series. Results of the double mass curves of all stations are almost a straight line as displayed in the example in Fig. 3,

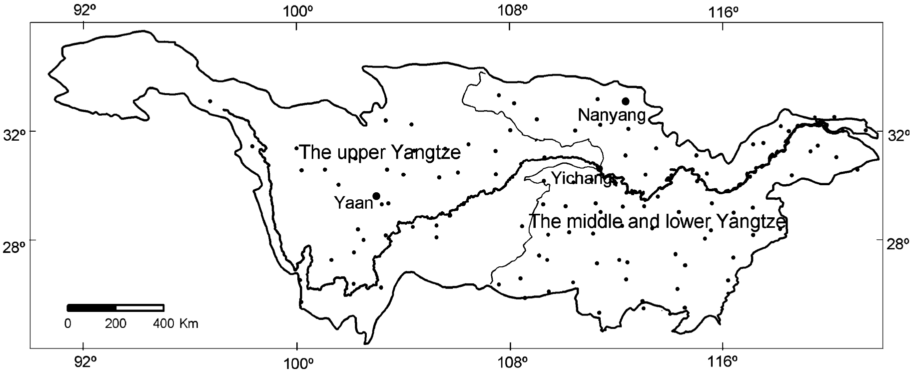

Fig. 2. Location of the observatory stations on the upper and the middle and lower Yangtze River basin

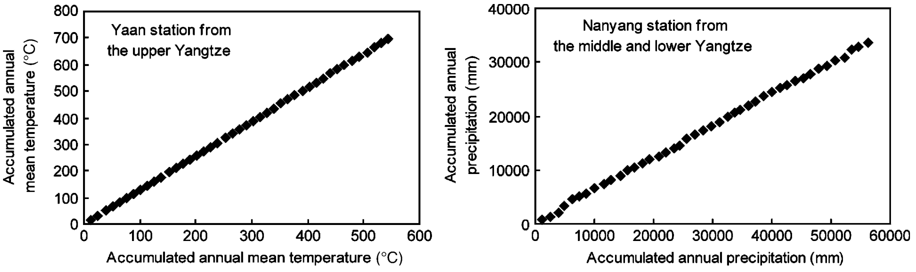

Fig. 3. The double-mass curve of the temperature series of the Yaan station from upper Yangtze and precipitation series of the Nanyang station from the Yangtze River basin

and no any obvious breakpoints are detected in time series of temperature and precipitation.

Student's T test can also be used to assess homogeneity by determining whether or not various samples are derived from the same population (Panofsky and Brier, 1968). In a homogeneous series, variations are caused only by the variation in weather and climate (Conrad and Pollak, 1950). Thus, modified series obtained through the subtraction of the reference series from the original series of each station should be more capable of detecting any inhomogeneity resulting from non-climatic factors. After filtering out the possible climatic abruption, T test was applied on each station basis and results reveal a wide range of the 95% confidence interval of the difference including zero. So, it is clear that there is no statistically significant variation or break point existing in the modified series.

Because the Yangtze River basin is characterized by different climate systems, the present study divides the Yangtze into two parts, the upper Yangtze reaches and the middle and lower Yangtze reaches. The summer monsoon dominated upper reaches is mainly characterized by a southwest current and the middle and lower reaches is characterized by a southeast current. The density of stations is lower in the high mountainous area, 37 stations are located on the upper Yangtze reaches covering a water system of about $100.6 \times 10^4\,\mathrm{km}^2$ (average altitude is about 2252 m a.s.l. from $90.6°\,\mathrm{E} \sim 111°\,\mathrm{E}$) along the upstream reaches of the Yichang hydrological station. Seventy-one stations are located along the middle and lower Yangtze reaches covering the water system of about $80 \times 10^4\,\mathrm{km}^2$ (average altitude is about 267 m a.s.l. from $111°\,\mathrm{E} \sim 121.8°\,\mathrm{E}$) (Fig. 2).

2.2 Methods

Extreme weather is defined by events which lie outside the normal range of intensity (Etkin, 1997) and can be identified by different thresholds in different places. In terms of the area under study, extreme cold and hot temperatures are respectively defined as below 0 °C and above 40 °C in most places (CWRC, 2002). However, temperatures above 40 °C is very rare and temperatures below 0 °C are common in the western parts of the upper Yangtze reaches. In order to enable this study to detect trends, in this region, hot and cold days are defined as daily maximum temperature $\geq 35\,°\mathrm{C}$ and minimum temperature $\leq -10\,°\mathrm{C}$. Days with maximum temperature $\geq 30\,°\mathrm{C}$ and minimum temperature $\leq 0\,°\mathrm{C}$ are also utilized to enable the regional comparison. An extreme precipitation event is defined, in conjunction with the regulations of the CMA, as 1-day precipitation $\geq 50\,\mathrm{mm/d}$. In contrast, dry days are defined as the 1-day precipitation $\leq 0.1\,\mathrm{mm/d}$.

According to the above definition, data sets have been constructed for each station: These datasets include annual and seasonal mean maximum and minimum temperature series, obtained by calculating arithmetic average of daily value and seasonal 1-day extreme temperature series defined by the highest and lowest daily value of corresponding period; the number of days with a daily maximum temperature $\geq 35\,°\mathrm{C}$ (and $\geq 30\,°\mathrm{C}$) and daily minimum temperature $\leq -10\,°\mathrm{C}$ (and $\leq 0\,°\mathrm{C}$); annual and seasonal precipitation, annual 1-day maximum, 3-day maximum, 7-day maximum precipitation, the number of days with precipitation $\geq 50\,\mathrm{mm}$ and the annual maximum number of consecutive dry days ($\leq 0.1\,\mathrm{mm}$). Drought events, in most cases, are defined by the variance of summer precipitation anomaly. However, droughts over the Yangtze River basin occur frequently in spring and autumn, so the ratio between the anomaly ($\Delta \mathrm{R}$) and its standard deviation (δ) for accumulated precipitation from March to November rather than that of summer precipitation is used as a drought index. The larger the index, the more severe the drought. A drought year is defined as $\Delta \mathrm{R}/\delta \geq 0.33$ as was stated in studies by CWRC (2002).

The trend tests applied in this study are both the nonparametric Mann-Kendall test (Kendall and Gibbons, 1981) and the simple linear regression method. MK analysis is a rank-based procedure suitable for detecting non-linear trend. Here, MK analysis is performed on the stations to detect positive or negative trends in extreme temperature and precipitation events and simple linear regression is applied to analyse the rate per decade (slope of the linear trend) by way of least squares.

3. Analysing results

3.1 Observed temperature trends

3.1.1 Mean maximum and minimum temperature

From a Yangtze basin-wide point of view, it is observed (Table 1) that statistically significant positive trends exist in both the annual mean maximum temperature (at 90% confidence level) and minimum temperature (at 95% confidence level). Since the positive trend in mean minimum temperature prevails over that of mean maximum, the diurnal temperature range has decreased in the last 40 years. Seasonal mean maximum temperature shows a slight decrease in summer, but mean minimum temperature reveals an increase in all seasons. The significant positive trend for maximum temperature exists in autumn and for minimum temperature it exists in autumn and winter. The negative trend in the diurnal temperature range is evident in summer and winter due to the opposite tendency or different magnitudes of the maximum and minimum temperature trend.

Due to the influence of various landforms, vegetation, urbanization and climate systems, maximum and minimum temperature variations in the Yangtze show large regional differences. Figure 4 illustrates the percentage of stations which show a significant trend beyond the 95% confidence level on the upper Yangtze reaches and the middle and lower Yangtze reaches, respectively. It can be seen that significant trends of minimum temperature are greater than those found for maximum temperature. The annual mean minimum temperature series shows a rising trend at 35% of stations and a falling trend at 11% of stations on the upper Yangtze reaches, and at 75% of stations and 1.4% of stations on the middle and lower Yangtze reaches. The annual mean maximum series shows a rising trend at 13% of stations and a falling trend at 5.4% of stations on the upper Yangtze reaches, and at 38% and 1.4% of stations on the middle and lower Yangtze reaches, respectively.

Table 1. Mann-Kendall (MK) statistics for mean maximum and minimum temperature in the Yangtze for 1960–2002

	Spring	Summer	Autumn	Winter	Annual
Mean maximum temperature	0.83	−0.95	1.43*	0.89	1.29*
Mean minimum temperature	1.25	0.66	1.45*	3.13**	2.75**
Diurnal variability	0.09	−2.58**	0.55	−2.04**	−1.96**

* denotes pass 90% confidence level; ** denotes pass 95% confidence level

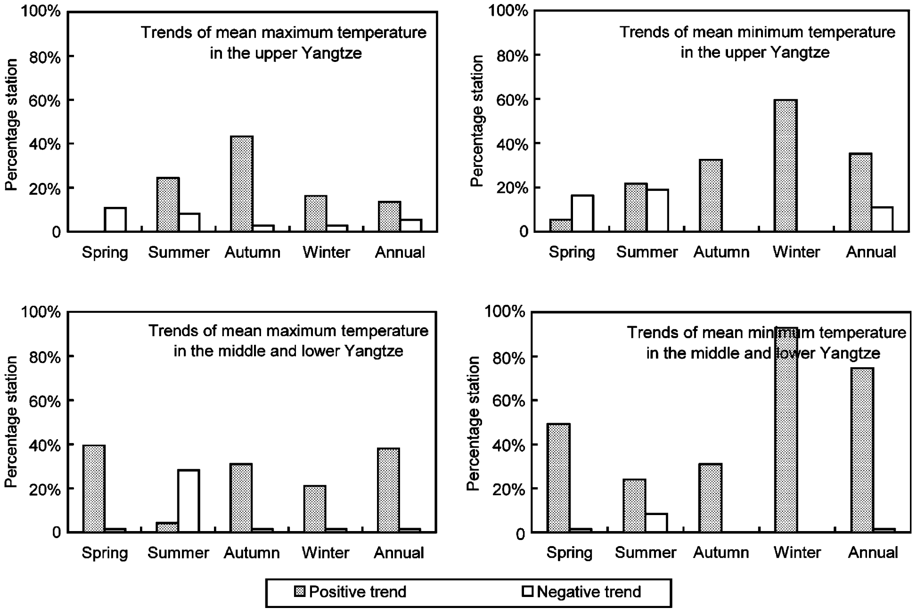

Fig. 4. Percentage of station shows significant trend for mean maximum and minimum temperature in Mann-Kendall (MK) test in 1960–2002

For the different seasons, the greatest number of positive trends are observed in the winter for mean minimum temperature for both the upper and the middle and lower Yangtze reaches. No decreasing trend was found and the number of stations showing a rising trend is up to 60% and 93% on the upper and the middle and lower Yangtze reaches, respectively. In winter mean maximum temperature, however, a rising trend is observed at only 16% of stations and a falling trend at 1.4% of stations on the upper Yangtze reaches, and at 21% and 2.7% of stations on the middle and lower Yangtze reaches, respectively. On the other hand, the greatest number of negative trends was observed in the summer mean maximum temperature for the middle and lower Yangtze reaches. The number of stations showing a rising trend is 24% of stations and a falling trend at 8% of stations on the upper Yangtze reaches, while 4.2% of stations show a rising trend and 29% of stations show a falling trend on the middle and lower Yangtze reaches. In summer, the mean minimum temperature shows a rising trend at 22% of the stations and a falling trend at 16% of stations on the upper Yangtze reaches, and at 24% and 8.4% of stations on the middle and lower Yangtze reaches, respectively.

The trend in the autumn temperature series is similar for both the mean maximum and mean minimum temperature with the number of stations showing a rising trend outnumbering those revealing a falling trend on the upper Yangtze and the middle and lower Yangtze reaches alike. More than 30% of stations show a rising trend and less than 3% of stations show a decreasing trend. The trend of the temperature series in spring is similar for both the mean maximum and mean minimum temperatures, but there is an obvious difference in the spatial distribution. The number of stations showing a falling trend is greater on the upper Yangtze reaches than for the middle and lower Yangtze reaches. The reverse is the case for the number of stations showing an increasing trend.

To summarize the daily maximum and minimum temperature trend of the Yangtze as identified by the MK test is predominated by a positive trend except for spring mean maximum and minimum temperature on the upper Yangtze reaches and the summer mean maximum temperature on the middle and lower Yangtze reaches. The greatest upward trend for mean maximum temperature appears in autumn on the upper Yangtze reaches, in spring on the middle and lower Yangtze reaches. For mean minimum temperature the greatest increasing trend is found in the winter for both the upper Yangtze and the middle and lower Yangtze reaches.

3.1.2 Extreme maximum and minimum temperature

Trends of seasonal 1-day extreme temperature as identified by the MK test show (Fig. 5) that a positive trend is prevalent in extreme maximum and minimum temperature, but to ranging degrees. For extreme maximum temperature, a significant positive trend exists only in spring on the middle and lower Yangtze reaches, while extreme minimum temperature shows a significant positive trend in summer and in winter on both the upper and the middle and lower Yangtze reaches. A weak negative trend is only identified for maximum extreme temperature in winter on the upper Yangtze reaches, and in summer and winter on the middle and lower Yangtze reaches.

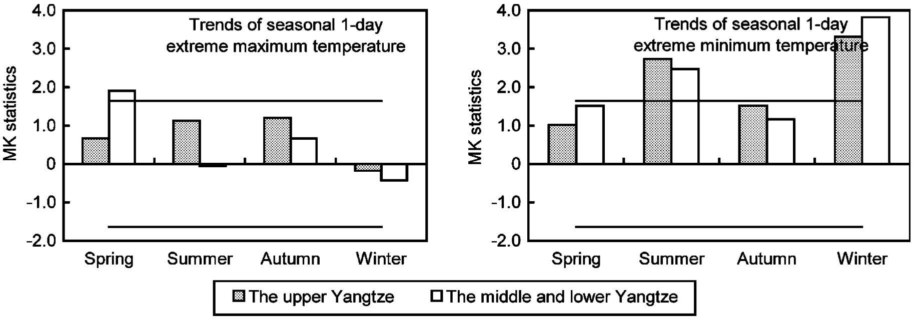

Fig. 5. Mann-Kendall (MK) test trend of seasonal 1-day extreme maximum and minimum temperature on the upper and the middle and lower Yangtze reaches in 1960–2002 (The solid lines in the figure denote 95% confidence level)

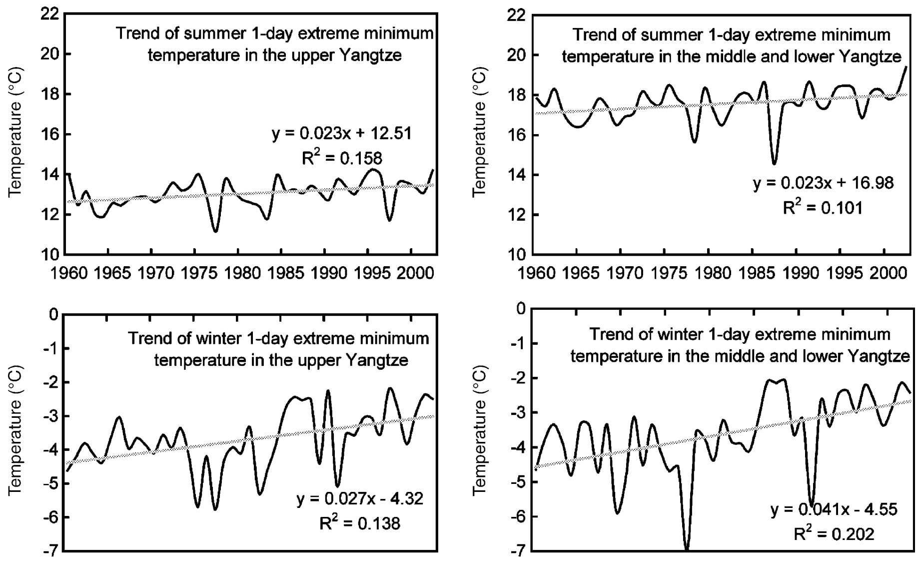

Fig. 6. Linear trend of seasonal 1-day minimum temperature in the summer and winter on the upper Yangtze and the middle and lower Yangtze reaches from 1960–2002

The linear variation of the seasonal 1-day extreme temperature has also been calculated and the time series has been plotted with decisive coefficient $R^2 \geq 10\%$ (Fig. 6). As shown, the upward trend of 1-day extreme temperature is apparent for summer and winter minimum temperatures, both on the upper and the middle and lower Yangtze reaches. The rate of increase is 0.2 °C/10a for summer minimum temperature on the upper and the middle and lower Yangtze reaches alike, while up to 0.3 °C/10a and 0.4 °C/10a for winter minimum temperature on the upper and the middle and lower Yangtze reaches, respectively.

3.1.3 Number of days with extreme temperature

Days with a maximum temperature higher than 35 °C (or 30 °C) and minimum temperature lower than −10 °C (or 0 °C) exist mainly in summer and winter seasons. Over the past 40 years, hot days ≥35 °C show a slightly negative trend in the Yangtze. Meanwhile, the frequency for daily value ≥30 °C display a minor positive trend on the upper Yangtze reaches, but a negative trend on the middle and lower Yangtze reaches. As for cold days, with minimum temperatures ≤−10 °C or ≤0 °C, a negative trend is significant

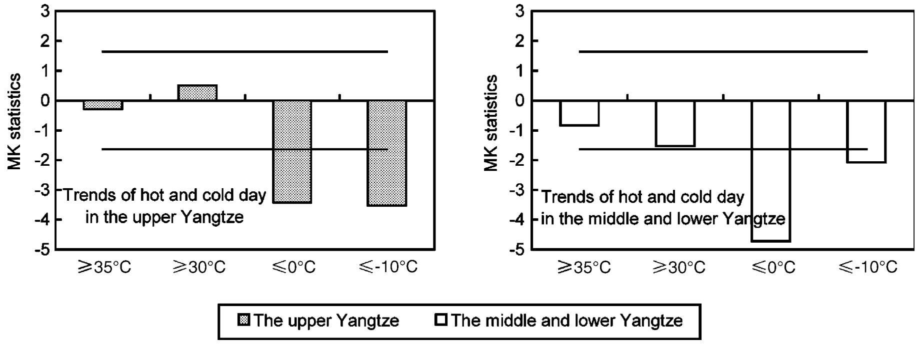

Fig. 7. Mann-Kendall (MK) test trend of hot days and cold days on the upper and the middle and lower Yangtze reaches from 1960–2002 (The solid lines in the figure denote 95% confidence level)

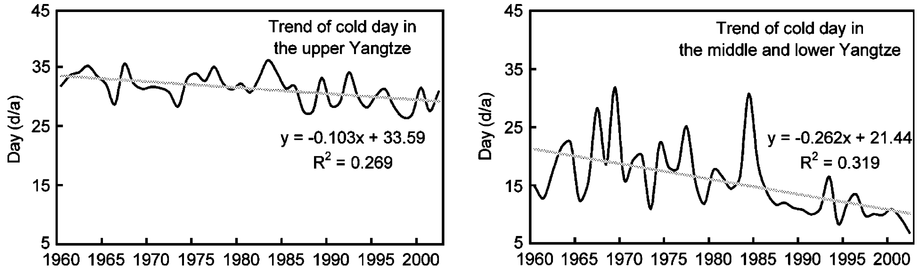

Fig. 8. Linear trend for extreme cold day ≤0 °C on the upper and the middle and lower Yangtze reaches from 1960–2002

on both the upper Yangtze and the middle and lower Yangtze reaches (Fig. 7). When the linear variation is calculated (Fig. 8), it can be seen that the number of cold days (≤0 °C) decrease at a rate of 1.0d/10a on the upper Yangtze reaches, and 2.6d/10a on the middle and lower Yangtze reaches. In addition, this decreasing trend has been more pronounced since the mid-1980s.

3.2 Observed precipitation trends

The variation of the mean value is in direct relation with extreme events. Large differences between the trend in annual precipitation and rainfall frequency can be used as an index of the change in rainfall intensity. Therefore, it is useful to identify the extreme events in the context of variation of mean values (Zhai and Pan, 2003).

3.2.1 Annual and seasonal precipitation

The results of MK trend analyses, based on selected gauging stations in the present study reveals (Table 2) a marked increasing trend in annual precipitation in the Yangtze River Basin. Significant increases are found in summer and winter, while spring and autumn witness a decreasing trend at the same period from 1960–2002. These findings are consistent with results from other researches (Gemmer et al., 2004; Ren et al., 2005). The significant negative trend in autumn precipitation on the upper Yangtze reaches, and the significant positive trend in summer precipitation on the middle and lower Yangtze reaches have also been detected e.g. Becker et al. (2003) and Shen (2005).

When further tested by the linear trend, the strongest trend in seasonal precipitation in the Yangtze basin is observed in summer. This upward trend equates to a rate of 19.1 mm/10a basin wide, and up to 28 mm/10a on the middle and lower Yangtze reaches (Fig. 9). Summer precipitation has increased by 112 mm in the last 40 years on the middle and lower Yangtze reaches. The contribution of summer precipitation to the annual total has also increased. In the 1960s it accounted for 37.9% of the annual amount, but

Table 2. Mann-Kendall (MK) statistics for annual and seasonal precipitation in the Yangtze for 1960–2002

	Spring	Summer	Autumn	Winter	Year
The upper Yangtze reaches	0.37	1.27	−2.08**	2.75**	0.78
The middle and lower Yangtze reaches	−0.95	2.63**	−1.62*	2.15**	1.04
Whole basin	−0.81	2.47**	−2.27**	2.33**	0.93

* denotes pass 90% confidence level; ** denotes pass 95% confidence level

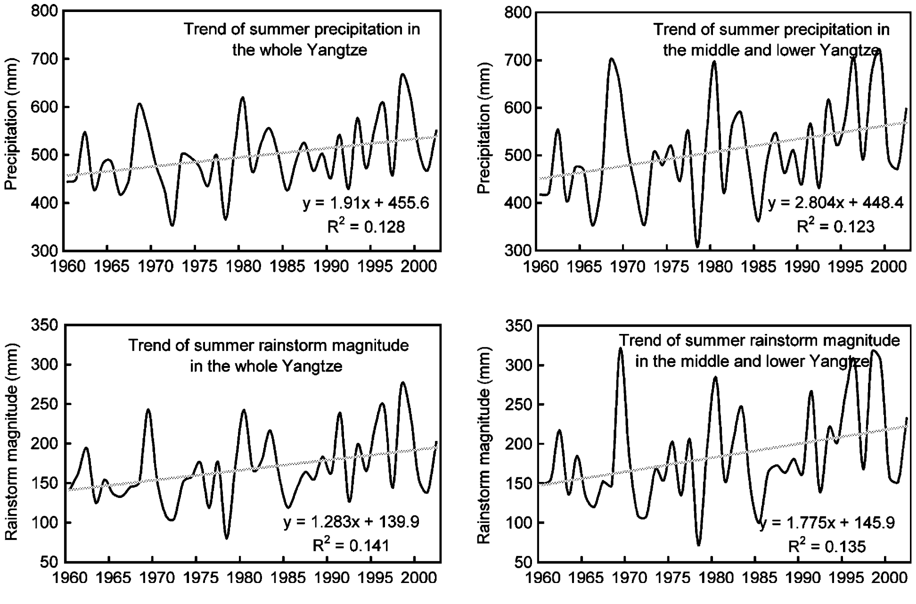

Fig. 9. Linear trend for summer precipitation and summer rainstorm magnitude in the whole Yangtze and the middle and lower Yangtze reaches from 1960–2002

this increased to 42.3% in the 1990s on the middle and lower Yangtze reaches. In addition, the trend of total rainstorm amount in the summer season also shows a significant positive tendency, with an increasing rate of 12.8 mm/10a and 17.7 mm/10a for the whole basin and the middle and lower reaches, respectively (Fig. 9). Summer rainstorm amount increased by 71 mm on the middle and lower Yangtze reaches from 1960–2002, accounting for more than 63% of summer precipitation contribution. The increase in the frequency of heavy rain events during the summer enhances the increasing contribution of summer rainfall to the annual precipitation totals in the Yangtze region.

3.2.2 Maximum precipitation and droughts

From a basin-wide perspective, MK analysis is performed at each station to test the trends of the annual 1-day, 3-day and 7-day maximum precipitation totals. The results reveal only 13%–15% of stations show a significant positive trend, and that 6–8% of stations show a significant negative trend at the 95% confidence level. When 1-day, 3-day and 7-day maximum precipitation totals are averaged across the two study areas no statistically significant trend is observed. The 1-day, 3-day and 7-day maximum precipitation totals show a slightly positive trend on the middle and lower Yangtze reaches, while 3-day and 7-day maximum precipitation reveal a weaker negative trend on the upper Yangtze reaches (Fig. 10).

As for drought spell, the annual maximum number of consecutive dry days between March and November do not show a statistically meaningful trend for most stations of the Yangtze from 1960–2002. Fourty-six % and 54% of stations showing a positive and a negative trend, respectively on the upper Yangtze reaches, but only 11% and 22% of stations are statistically significant. On the middle and lower Yangtze reaches, 66% and 34% of stations show a positive trend and a negative trend, respectively, but only 6% and 3% of stations are statistically significant at the 95% confidence level. The regional averaged value of the upper Yangtze reaches however, show a significant negative trend with a slope of 0.7d/10a, while on the middle and lower Yangtze reaches, the tendency is very weak (Fig. 11).

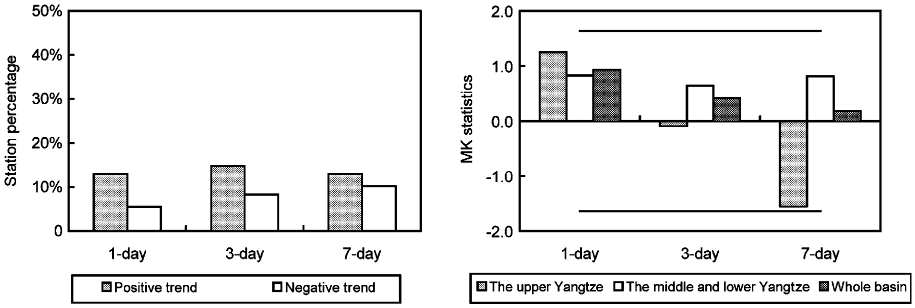

Fig. 10. Annual 1-day, 3-day, 7-day extreme precipitation trend in 1960–2002: Former panel: Percentage of stations show significant trends in the whole basin; Latter panel: the Mann-Kendall (MK) statistics on the upper, the middle and lower Yangtze reaches and whole basin (The solid lines in the figure denote 95% confidence level)

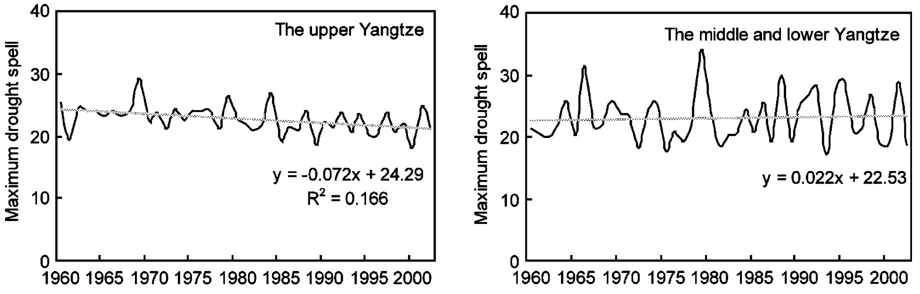

Fig. 11. Trends of maximum drought spell between March to November on the upper and the middle and lower Yangtze reaches from 1960–2002

3.2.3 Days of extreme precipitation and index of droughts

As shown in Fig. 12, the frequency of normal precipitation events (0.1–50 mm/d) show a distinct negative trend in autumn and a positive trend in spring and winter on the upper Yangtze reaches. These findings agree with the seasonal precipitation trends (Table 2) and indicates that the trends of seasonal precipitation on the upper Yangtze reaches are determined mainly by the variation of normal events in seasons except summer. On the middle and lower Yangtze reaches, a distinct negative trend in precipitation in the autumn, and a positive trend in winter (Table 2) can also be explained by the frequency of normal events (Fig. 12). During the summer season, the slight increase of precipitation on the upper Yangtze reaches and significant increase of precipitation on the middle and lower Yangtze reaches, results mainly from the variation of extreme events. This variation follows a weaker positive trend on the upper Yangtze reaches and a strong positive trend on the middle and lower Yangtze reaches. The rate of the linear trend is 0.21d/10a and 0.26d/10a for summer and annual extreme precipitation events respectively on the middle and lower Yangtze reaches. In summary, annual extremes have increased 1 day per station over last 40 years on average and summer extremes are the main contributor to this increase (Fig. 13).

In terms of the drought situation, Fig. 14 is produced by calculating the drought index for each station and by creating a regional average. As illustrated, the percentage of stations experiencing droughts per year from 1960–2002 in the Yangtze indicates that the drought stricken area on the upper Yangtze reaches has not shown any observed monotonic trend, whilst on the middle and lower Yangtze reaches the number of droughts have decreased slightly. For the majority of stations the drought index has not exhibited any obvious trend. Sixteen percent of stations have shown a statistically significant positive trend and 11% of stations have shown a negative trend on the upper Yangtze reaches. Along the middle and lower Yangtze reaches, no station has been found to exhibit a positive trend and 8% of stations have shown a negative trend. The changes of the regional scale drought index (Fig. 14) are similar to the variation of the percentage of stations experiencing a drought year. The period 1975–1990 is characterized by a high degree of variation. The two periods pre- and post-1975–1990 (1965–1974 and 1991–1998) reveal positive trends in the number of stations experiencing droughts as the upper Yangtze reaches. Across the middle and lower reaches of the

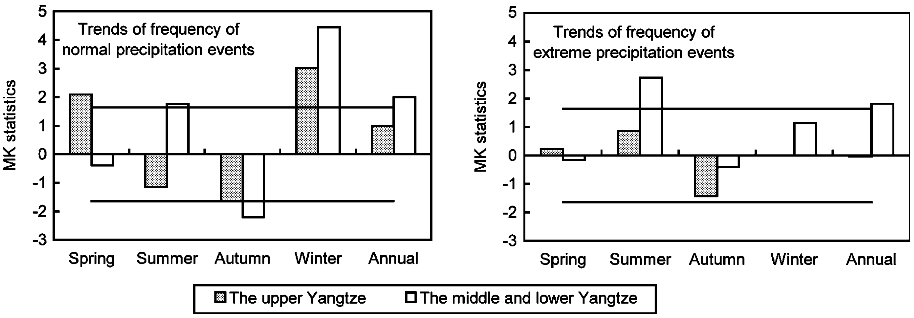

Fig. 12. Mann-Kendall (MK) test trend for the normal and extreme precipitation events on the upper Yangtze and the middle and lower Yangtze reaches from 1960–2002

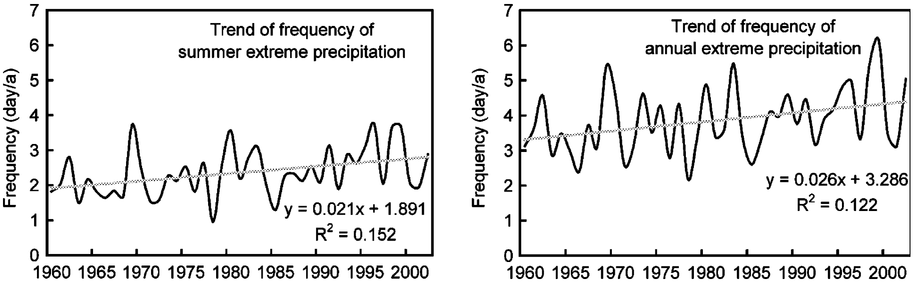

Fig. 13. Linear trend for the summer and annual extreme precipitation events on the middle and lower Yangtze reaches from 1960–2002

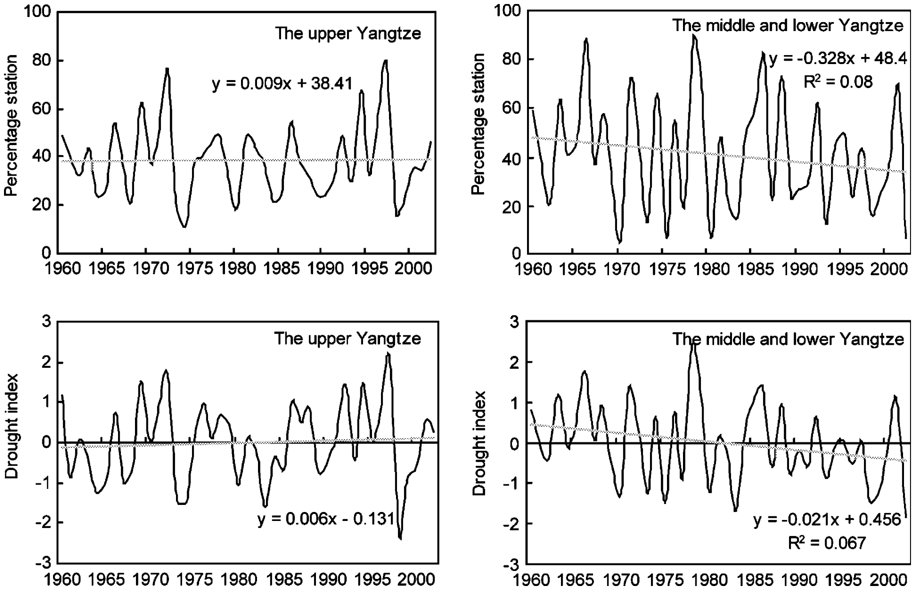

Fig. 14. Drought events on the upper and the middle and lower Yangtze reaches from 1960–2002. (upper panel: percentage of stations experience drought year; lower panel: drought index)

Yangtze, the number of stations experiencing droughts has been declining since the mid-1980s.

4. Conclusions and discussions

According to IPCC Third Assessment Report (IPCC, 2001), a significant reduction in the frequency of extreme low monthly and seasonal temperatures across large parts of the globe has been observed since the late 19th century. In addition to the changes in extreme temperatures a 2–4% increase in the frequency of heavy precipitation events has been reported across the mid and high latitudes of the Northern Hemisphere during the latter half of the 20th century. Many findings from the present study are consistent with the IPCC reports as the regional response of the Northern Hemisphere to global warming. Across the Yangtze River basin, both annual mean maximum and minimum temperatures show a significant positive trend, with the increasing tendency of minimum temperature being much larger than that identified for maximum temperature and results in an observed decreasing trend of the diurnal temperature range. By testing the trend of seasonal 1-day extreme temperature, a slight reduction of the seasonal extreme maximum temperature over Yangtze in the summer, and the obvious reduction of the extreme minimum seasonal temperature over the Yangtze in winter and autumn has been observed. In addition, the number of hot days ($\geq 35\,^{\circ}$C) has decreased slightly, while the number of cold days ($\leq -0\,^{\circ}$C and $\leq -10\,^{\circ}$C) has decreased significantly. These trends are synchronous across the whole basin, but are emphasized on the middle and lower Yangtze reaches.

The decreasing trend in the number of rain days with precipitation ≥ 50 mm in China is accompanied by a significant increase in the proportion of mainland China affected by extremely high rainfall intensities (Zhai et al., 1999). In the Yangtze, however, the 1-day, 3-day and 7-day maximum precipitation magnitude has not shown any obvious trends, but displays a slight positive trend on the basin-wide scale. Though the trend of heavy rain intensity is not statistically significance, the number of days with rainstorm ≥ 50 mm displays, an average, significant positive trends. The upward trend of rainstorm frequency on the middle and lower reaches is the main contributor to the increase in summer precipitation in the Yangtze. Meanwhile, the regional maximum drought spell between March and November has significantly decreased on the upper Yangtze reaches, while no monotonic trend has been found on the middle and lower Yangtze reaches. The intensity of the drought index reveals an appreciable weak negative trend existing on the middle and lower Yangtze reaches, while no trend has been detected on the upper Yangtze reaches.

To summarize, changes of climatic extremes in the Yangtze from 1960-2002 reflect the weakening of extreme temperature events and drought events, but the enhancement of climate induced flood hazard has to be expected if the observed trends of last 40 years prevail in future. However, these observational findings are based on relatively short periods and results cannot be considered as a sufficient evidence of climate change.

What has to be mentioned here is that the above results can provide no evidence or indication of the future persistence of observed trends, or proof of climate extremes changing in the context with climate warming. Various climate models can project the evolutions of surface air temperature or precipitation under different scenarios. Previous studies (e.g. Gao et al., 2001, 2002) on the impacts of greenhouse effects upon climate change over China as simulated by regional climate models (RCM), which provide better representations of regional climate variation than general circulation models (GCM), indicate that the correlation between simulated annual mean temperature and precipitation with observational series from 1961–1990 is high, up to 0.94 and 0.8, respectively according to the analysis of the control run (Gao et al., 2001). A sensitivity study with doubled CO_2 concentration reveals that a statistically significant increase in daily maximum and daily minimum temperatures are associated with a decreasing diurnal temperature range due to the higher increase of minimum temperature and significant decrease in the number of cold spell days in winter (Gao et al., 2002). As for precipitation events, significant increases in the number of heavy rain days in southeast China was simulated by RCM (Gao et al., 2002), and a significant wetter trend of summer rainfall over eastern China was also predicted by HadCM2 (Gong and Wang, 2000).

Most parts of the Yangtze are characterized climatically by the subtropical monsoon climate, which is a product of alternating seasonal airmass movements between the continent and the ocean generated by the land/sea thermal contrast. The monsoon activity not only influences the spatial and temporal variation of precipitation, but also the temperature over the Yangtze. The intensity of the summer monsoon is negatively correlated with summer temperature of Northern China and positively correlated with that of the middle and lower Yangtze reaches (Guo et al., 2003). A recent study by Qian et al. (2003) shows that, since the late 1970s, the summer temperature in Inland Asia has become cooler and the temperature over the oceans surrounding the continent has become warmer. The weakened thermal contrast has lead to the weaker summer monsoon experienced in recent decades and the persistence of the rain belt over Southern China. This might be the result of the weaker increase of summer temperature in the Yangtze than in Northern China (Wang et al., 2003) and the abundant precipitation the region received during this period.

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