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Climate change or variability? The case of Yellow river as indicated by extreme maximum and minimum air temperature during 1960–2004

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With 8 Figures

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Summary

The spatial and temporal variability of winter extreme low-temperature events and summer extreme high-temperature events was investigated using daily air temperature series (1960–2004) from 66 sites in the Yellow River basin, China, with the help of Mann–Kendall trend test method. In this study an extreme temperature event is defined by exceeding or falling below various threshold values of daily maximum and daily minimum air temperature: 90th percentile, 95th percentile for the high-temperature events; 10th percentile and 5th percentile for the low-temperature events. The analysis results indicate that: 1) significant upward trend of frequency and intensity of the high-temperature events is found in the stations in the west and north part of the Yellow River basin, but trends in most stations in the middle and lower Yellow River basin are not significant at >95% confidence level; 2) almost the whole Yellow River basin is dominated by the significant downward trend of frequency of the cold events. Stations featured by the increasing winter minimum temperature are also more than those featured by changing summer maximum temperature; and 3) annual warming trend in the Yellow River basin mainly results from the increase in winter minimum temperature. Significant warming in the upper reach of the Yellow River will be likely to threaten the availability of the water resource in the whole basin, which should draw certain concerns from local policy-makers and water resource management agency in the region.

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1. Introduction

Climatic variability combining with human-induced emission of green-house gases results in an increase in global mean temperature (IPCC 2001), which in turn, leads to higher evaporation rates and transports larger amounts of water vapor into atmosphere, probably having accelerated the global hydrological cycle (Menzel and Bürger 2002). Meanwhile, public awareness of extreme climatic events has risen sharply in recent years partly because tremendous concerns are drawn on the catastrophic nature of floods, droughts, storms and heat waves or cold spells (e.g. Beniston and Stephenson 2004; Zhang et al. 2006a, b). Temperature extremes exert considerable influences not only on processes in nature but also on different aspects of socio-economic activities. Projected global climate change will probably further accelerate the global hydrological cycle, which in turn will alter the spatial and temporal distribution of the flood/drought hazards in both the global and regional scales. More and more research results indicate that extreme high temperatures and prolonged heat waves can damage agricultural production, increase energy and water consumption and also exert negative impacts on human well-being and even on human health (Karl and Easterling 1999; Kunkel et al. 1999; Easterling et al. 2000; Nasrallah et al. 2004).

An increase in global air temperature between 0.4 and 0.8 °C has occurred since the late 19th century, which generally attributed to the increasing concentration of atmospheric greenhouse gases emitted by human activities (Jones et al. 1999; Nasrallah et al. 2004). Studies also indicate an increase of extreme warm events in the past decades, especially since 1983 (WMO 1997; Easterling et al. 2000). However this increase in temperature extremes is different from region to region. Bonsal et al. (2001) performed an analysis on the spatial and temporal variability of extreme temperature in Canada for the period of 1950–1998 and found great regional and seasonal differences. Seasonal differences in changes of the temperature extremes are also identified in the 105-year (1897–2001) surface air temperature record of the National Observatory of Athens (NOA), indicating a tendency toward warmer years with significantly warmer summer and spring periods and slightly warmer winters (Founda et al. 2004). Different changing trends are found in the occurrence frequency of the hot days and cool days. Manton et al. (2001) found significant increases in hot days and warm nights, and decreases in cool days and cold nights since 1961 across Southern Asia and the South Pacific region. Analyses of the 20th century trends of extreme hot or cold weather events in the United States, however, showed no significant changes in frequency or intensity (Kunkel et al. 1999; Nasrallah et al. 2004). As for the extreme temperature changes in China, Zhai and Pan (2003) studied the changes in the frequency of some extreme temperature events based on the daily surface air temperature data from about 200 stations during 1951–1999 in China, showing that the number of hot days (over 35 °C) displays a slightly decreasing trend, while the number of frost days (below 0 °C) exhibits a significantly decreasing trend. Meanwhile, increasing trends were detected in the frequencies of warm days and warm nights, and decreasing trends were found in the frequencies of cool days and cool nights in China. Yan et al. (2002) analyzed ten of the longest daily temperature series presently available in Europe and China, and three periods of changes in temperature extremes were identified: decreasing warm extremes before the late

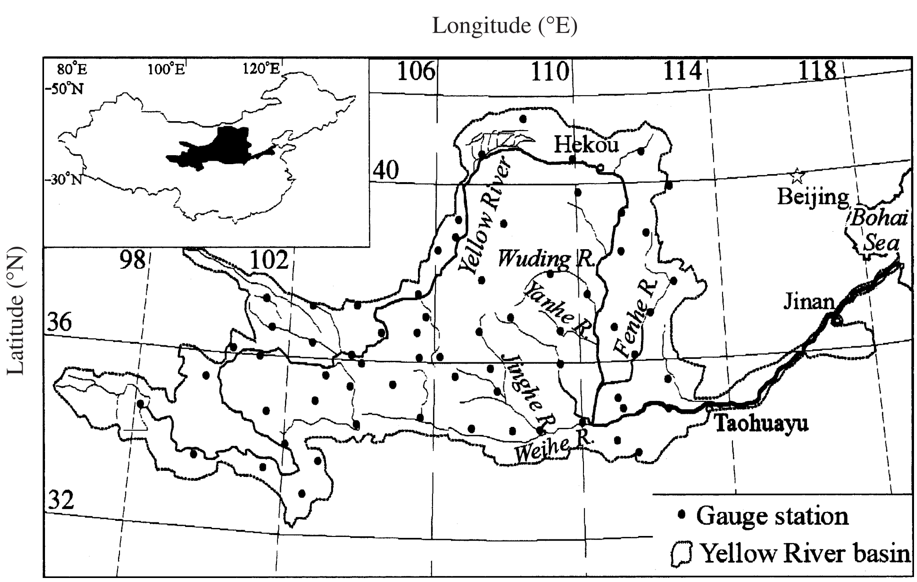

Fig. 1. Location of the Yellow River basin and meteorological stations used in the study

19th century, decreasing cold extremes since then and increasing warm extremes since 1960s.

The Yellow River (Huang He) (95°53′ E–119°5′ E; 32°10′ N–41°50′ N) (Fig. 1) being the second largest river in China and the fifth largest river in the world, has a length of 5464 km with an area of 752440 km^2, mainly flowing through the arid or semi-arid region. From the origination to Hekou is the upper reach, with the length being 3472 km; from Hekou to Taohuayu is the middle reach, with the length being 1206 km; and with the length of 786 km, the lower Yellow River is from Taohuayu to the mouth (Fig. 1). The altitude ranges from above 4000 m a.s.l. in the west to below 100–2000 m a.s.l. in the middle and lower reaches. The average annual precipitation in the basin is about 466 mm, and the annual pan-evaporation reaches from 700 to 1800 mm. Evaporation plays the important role in the availability of water resources in the Yellow River basin. The annual mean air temperature is 1–8 °C in the upper (west part) Yellow River basin, 8–14 °C in the middle Yellow River basin and 12–14 °C in the lower (east part) Yellow River basin. The Yellow River acts as the important source for water supply in the North-western China and Northern China; but it is also the area of shortage of water resources in China (Wang et al. 2001). The evaporation exerts significant impacts on availability of water resources in the Yellow River basin. The changes of spatial and temporal distribution of air temperature will alter the evaporation, which will further alter the water resources in the Yellow River basin. Therefore, it is greatly important to understand the spatial and temporal variability of the temperature changes, including the extreme temperature variability. To the best of our knowledge, reports concerning studies of temporal and spatial extreme temperature changes in the Yellow River basin are lacking. The objective of this paper is, therefore, to detect the trend of frequency and intensity of maximum/minimum air temperature events and their spatial aspects. The extreme temperature events are defined in this study by seasonally maximum or minimum temperature and temperature regimes exceeding or falling below certain percentile thresholds. The current research will be helpful in understanding the possible causes of climate change and the process of basin-scale water cycle.

2. Data and method

2.1 Data preparation

Daily maximum and minimum air temperature data series during 1960–2004 are collected to use in the analysis ("temperature" mentioned in the following sections refers to air temperature measured at, or otherwise converted to 1.5 m above ground surface). The meteorological stations with missing data exceeding 1 year are excluded from the data set, which results in 66 useful meteorological stations in the current study. Of which, 11 stations have missing data in 2–6 months and 6 stations have missing data in one day. In the first case the missing data are completed by their neighboring stations through the simple linear regression method with regression correlation coefficient $R^2 > 0.9$. In the second case, the missing data are filled in by the average value of its neighboring days.

In the current study, the *hot events* are defined as: 1) the seasonal maximum temperature, e.g. maximum daily temperature in June, July, and August, and 2) days with daily maximum temperature exceeding a certain percentile of daily extreme temperature, so-called POT analysis (peaks over threshold) (Bordi et al. 2006). The *frequency of hot events* is defined as days with daily maximum temperature exceeding 95th percentile (TX95) and 90th percentile (TX90), respectively during a certain time interval. The *hot intensity* is defined as the average maximum temperature exceeding a certain percentile threshold (95th percentile and 90th percentile). The *cold events* are defined as: 1) the seasonal minimum temperature, e.g. minimum daily temperature in January, February, and December and 2) days with daily minimum temperature falling below a certain percentile. The *frequency of cold events* is defined as days with daily minimum temperature falling below 5th percentile (TI5) and 10th percentile (TI10), respectively during a certain time interval. The *cold intensity* is defined as the average minimum temperature falling below a certain percentile (5th percentile and 10th percentile). The multi-annual mean maximum summer temperature and multi-annual mean minimum winter temperature are defined as the mean extreme temperature over the whole time period analyzed. The homogeneity of the extreme temperature series was analyzed by calculating the von Neumann ratio (N), the cumulative deviations ($Q/n^{-0.5}$ and $R/n^{-0.5}$), and the Bayesian procedures (U and A) (Buishand 1982). The data sets proved to be homogeneous at the significance level of 5%.

2.2 Method

The Mann–Kendall (MK) trend test (Mann 1945; Kendall 1975) is used to analyze the trends of the frequency of the hot/cold events, hot/cold intensity and seasonal maximum/minimum temperature for all the 66 stations in the Yellow River basin. The influence of serial correlation in the time series on the results of MK test has been discussed in the literature (e.g. Yue et al. 2002; Yue and Wang 2002). Prewhitening has been used to eliminate the influence of serial correlation (if significant) on the MK test in trend-detection studies of meteorological time series. However, the study conducted by Yue and Wang (2002) demonstrates that when trend exists in a time series, the effect of positive/negative serial correlation on the MK test is dependent upon sample size, magnitude of serial correlation, and magnitude of trend. When sample size and magnitude of trend are large enough, serial correlation no longer significantly affects the MK test statistics. In this study, before the MK test was applied, the series of the seasonal extreme temperature and hot/cold intensity were tested for persistence by the serial correlation analysis method presented in Haan (2002) using the following equation

$$\rho_m = \frac{\mathrm{Cov}(X_t, X_{t+m})}{\mathrm{Var}(X_t)} = \frac{\frac{1}{n-m}\sum_{t=1}^{n-m}(X_t - \overline{X})(X_{t+m} - \overline{X})}{\frac{1}{n-1}\sum_{t=1}^{n}(X_t - \overline{X})^2}$$

where X_t ($t = 1, 2, \ldots$) is the tested time series; X_{t+m} is the same time series with a time lag of m; $\overline{X}$ is the mean of the time series. The equation shows that $-1 \leq \rho \leq 1$, if $m = 0$ then $\rho = 1$. For a purely random (stochastic) series, $\rho_m \approx 0$ for all $m \neq 0$. If the series of ρ_m (for $m \neq 0$) falls between the 95% confidence interval calculated by $\frac{u}{l} = (-1 \pm z_{1-\alpha/2}\sqrt{n-2})/(n-1)$ (n is the length of the tested time series, l and u are the lower and upper limits, α is the significance level, 5% in this case, z is the critical value of the standard normal distribution for a given α), the tested series is an independent series at 95% confidence level.

3. Results

3.1 Multi-annual mean extreme temperature

Figure 2 demonstrates the spatial distribution of the multi-annual mean maximum summer temperature (Fig. 2A) and multi-annual mean minimum winter temperature (Fig. 2B). The lower and middle-southern Yellow River basin are dominated by higher multi-annual mean maximum summer temperature. The multi-annual mean maximum summer temperature in the lower Yellow River basin is about 40.2–43.7 °C. The upper Yellow River basin is characterized by lower multi-annual mean maximum summer temperature of about 22.9–33.7 °C. As for the spatial distribution of the multi-annual mean minimum winter temperature, about −15.6 to −9.5 °C in the lower Yellow River basin and about −22.1 to −18.5 °C and −33.1 to −27.5 °C in the north and upper Yellow River basin, respectively. Gen-

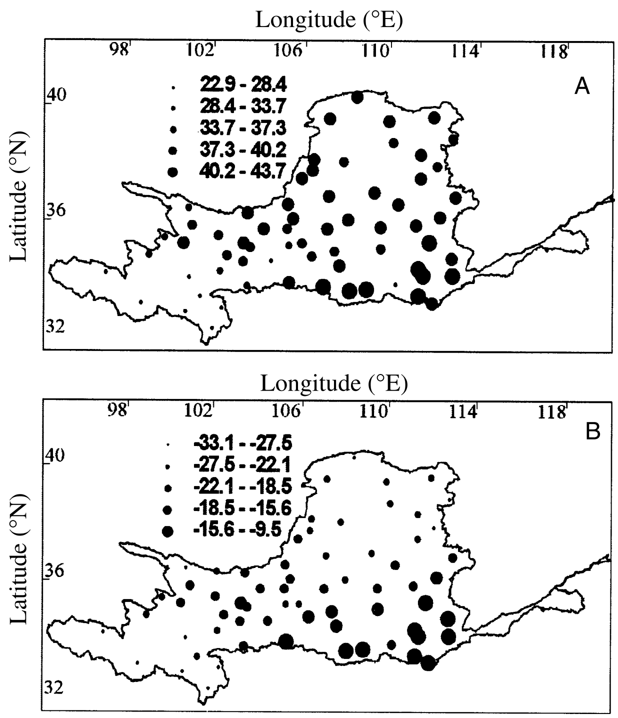

Fig. 2. Spatial distribution of the multi-annual mean maximum temperature (**A**) and multi-annual mean minimum temperature (**B**) in the Yellow River basin

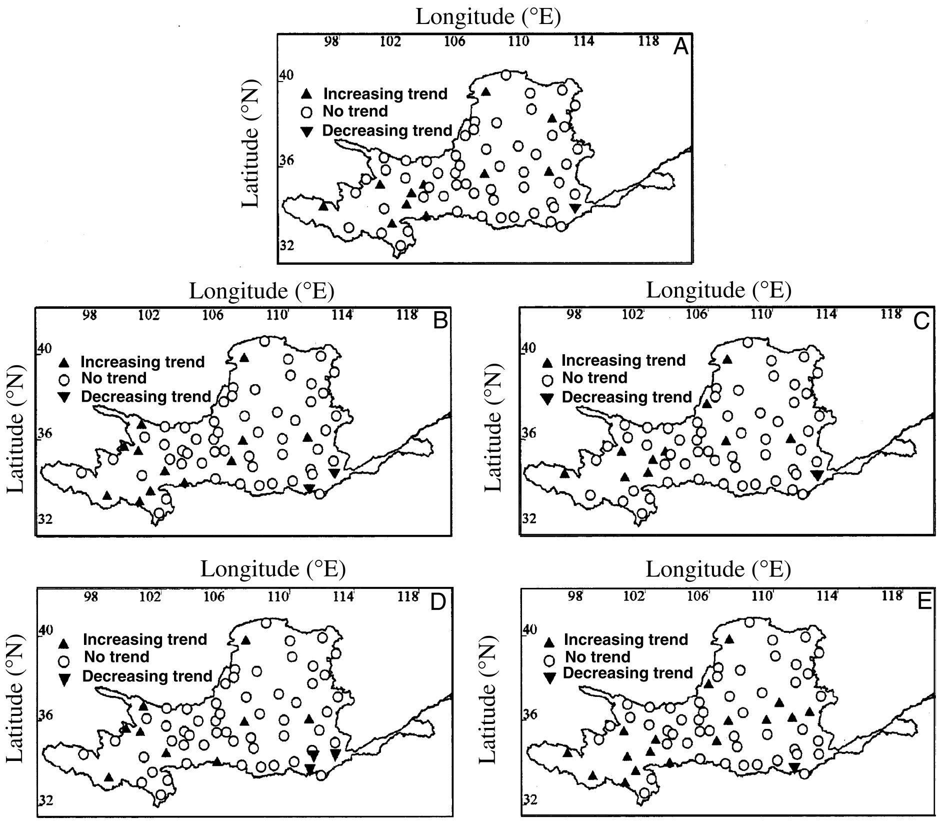

Fig. 3. Mann–Kendall trend of the maximum summer temperature (**A**), days of the summer temperature exceeding 95th percentile (**B**), summer temperature intensity exceeding 95th percentile (**C**), days of the summer temperature exceeding 90th percentile (**D**), and summer temperature intensity exceeding 90th percentile (**E**). Significance of the trend is identified by 95% confidence level

erally, the upper Yellow River basin is featured by lower multi-annual mean minimum winter and maximum summer temperature and the lower Yellow River basin is characterized by higher multi-annual mean minimum winter and maximum summer temperature. The middle Yellow River basin acts as the transitional zone.

3.2 Trends of maximum summer temperature

It can be seen from Fig. 3A that 1) in most stations of the Yellow River basin the maximum summer temperature (MST) has no significant upward or downward trend at >95% confidence level, 2) significant upward trend of MST at >95% confidence level only exists in several isolated stations in the middle and north part of the Yellow River basin, and 3) seven out of eleven stations having significant upward trend of MST at >95% confidence level are found in the western part of the Yellow River basin. The spatial distribution of MK trend of TX95 (Fig. 3B) is similar to that of MST (Fig. 3A) with no trend in most part of the basin. The frequency of TX95 is increasing in the west stations in the Yellow River basin and in some stations in the north and middle Yellow River basin at >95% confidence level. The TX95 hot intensity is found to be in significant upward trend in the western Yellow River basin at >95% confidence level. Most parts of the middle and lower Yellow River basin have no significant trend at >95% confidence level (Fig. 3C).

Figure 3D demonstrates the spatial distribution of the changing trends of the frequency of TX90. Similarly, most stations of the Yellow River have no significant trend of TX90. Stations in the western part of the Yellow River basin featured by significant upward trend of TX90 are less than the stations characterized by significant upward trend of TX95 (Fig. 3B). However, the stations featured by the significant upward trend at >95% confidence level in western and middle Yellow River basin in TX90 hot intensity (Fig. 3E) are little more than those featured by TX95 hot intensity (Fig. 3C). It can be tentatively concluded, for the maximum summer temperature, that the trends of frequency of warming events (Fig. 3B, D) and hot intensity (Fig. 3C, E) do not change significantly when the thresholds alter from 95th to 90th percentile. However, the stations of having significant trends in TX90 hot intensity are little more than those in TX95 hot intensity.

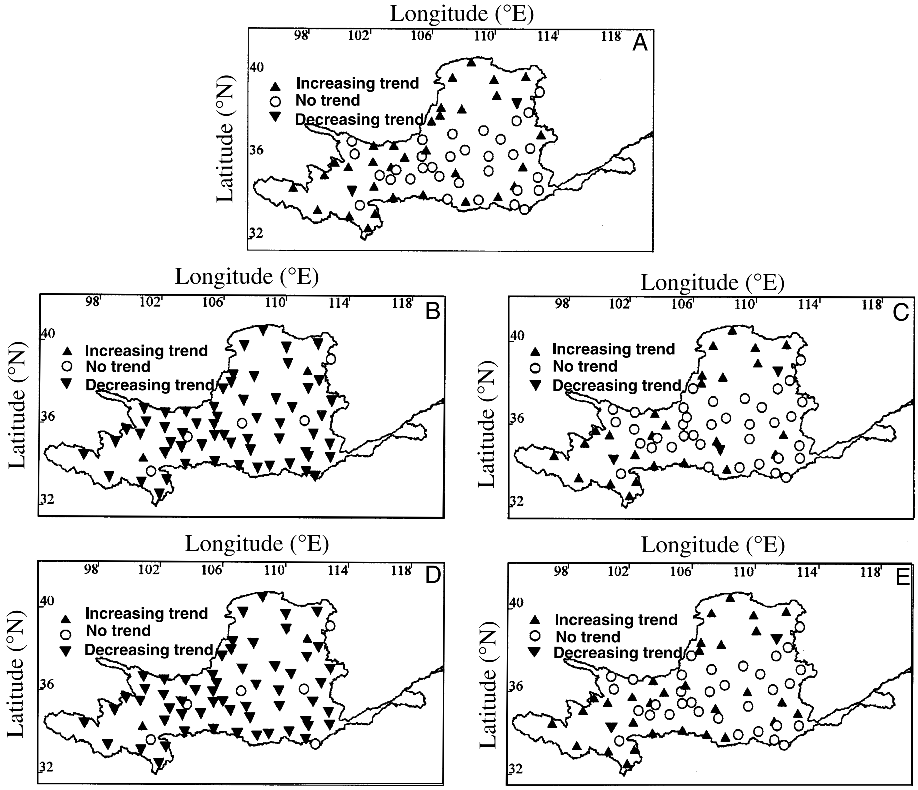

Fig. 4. Mann–Kendall trend of the minimum winter temperature (**A**), days of the winter temperature below 5th percentile (**B**), winter temperature intensity below 5th percentile (**C**), days of the winter temperature below 10th percentile (**D**), and winter temperature intensity below 10th percentile (**E**). Significance of the trend is identified by 95% confidence level

3.3 Trends of minimum winter temperature

Figure 4 illustrates the changing trends of winter minimum temperature, TI5, TI10 and the corresponding cooling intensity. It can be seen from Fig. 4A that north and west stations of the Yellow River basin are dominated by the significant increasing trend in winter minimum temperature, the stations featured by the significant increasing trends are much more than those featured by the significant increasing trends in summer maximum temperature (Fig. 3A). Some places in the lower Yellow River are featured by a significant upward trend of the winter minimum temperature at >95% confidence level. In the middle Yellow River basin, the changing trend of the winter minimum temperature is not significant at >95% confidence level. This result means that, in the north and west part of the Yellow River basin and some stations in the lower Yellow River basin, the winter is significantly warming and this changing trend is statistically significant at >95% confidence level. Number of days with winter minimum temperature falling below 5th percentile is decreasing (Fig. 4B). It can be seen from Fig. 4B that almost the whole Yellow River basin is dominated by the decreasing frequency of cold winter days, and this trend is significant at >95% confidence level. Only few isolated stations in the Yellow River basin are featured by increasing frequency of cold winter days. The reason for that is yet to be investigated. Figure 4C indicates that the mean minimum temperature falling below 5th percentile is increasing, and this upward trend is significant at >95% confidence level in the north and west parts of the Yellow River basin.

Both Fig. 4D and E show similar spatial patterns of the frequency of cold events and cooling intensity in winter if compared to those demonstrated in Fig. 4B and C. The frequency of cold events (days with daily minimum temperature in winter falling below 10th percentile) has a significant downward trend at >95% confidence level in almost the whole Yellow River basin. The mean minimum temperature over days with daily minimum temperature falling below 10th percentile is significantly increasing in the west, north and south-eastern Yellow River basin. The trend of TI10 is not significant in the middle and north-eastern part of the Yellow River basin.

Figure 5 shows the spatial patterns of the changing trends of the range of extreme temperature (the difference between the summer maximum and minimum temperature and the difference between winter maximum and minimum temperature) over the Yellow River basin for summer

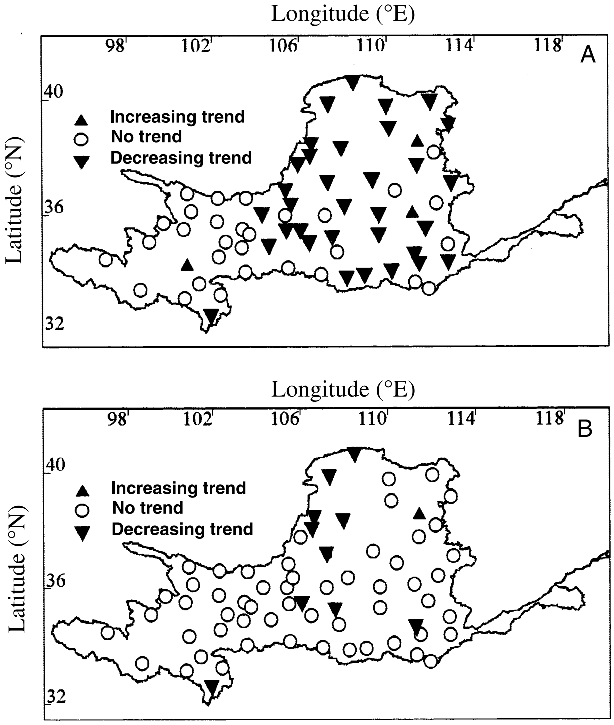

Fig. 5. Mann–Kendall trend of the range of summer temperature extremes (**A**) and range of winter temperature extremes (**B**). Significance of the trend is identified by 95% confidence level

(Fig. 5A) and winter (Fig. 5B). The range of extreme summer temperature is significantly decreasing in the middle and lower stations of the Yellow River basin, meaning that in these regions the summer minimum temperature has increased more than that of summer maximum temperature. The changing trend is significant at >95% confidence level. The insignificant trend at >95% confidence level is mainly found in the upper Yellow River basin. The winter extreme temperature range is not significantly decreasing or increasing for most parts of the river basin (Fig. 5B). Only some places in the north Yellow River basin witness a significant decreasing winter temperature range at >95% confidence level.

3.4 Temporal changes of the extreme temperature

Figure 6 shows the temporal changes in areal (basin-averaged) summer maximum and minimum temperature and winter maximum and minimum temperature over the Yellow River basin. The summer maximum temperature over the Yellow River basin ranges from 30 to 34 °C and the summer minimum temperature ranges from 14 to 18 °C. The curves of 5-year moving averages indicate that the summer maximum and minimum temperature are increasing after early 1990s. The simple linear regression result indicates a slightly increasing/decreasing trend of the summer maximum/minimum temperature, but not significant at 95% confidence level. Significant upward trend at >95% confidence level can be found in the winter maximum and minimum temperature series over the Yellow River basin. Therefore, the warming in the Yellow River basin, as reported by many researchers (e.g. Chen and Zhu 1998; Ren et al. 2005), is mainly induced by the significantly increasing winter temperature.

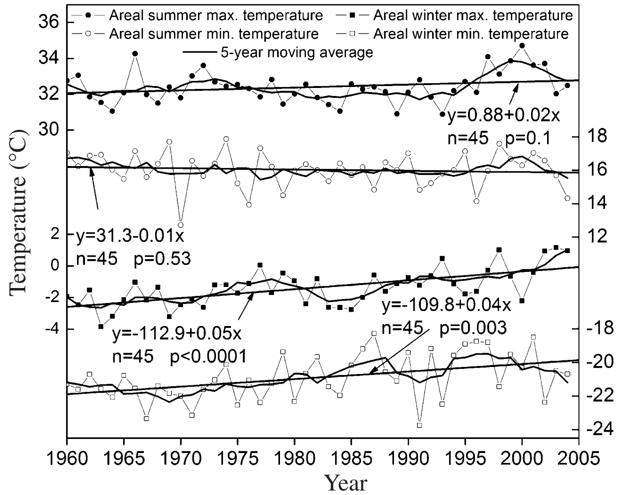

Fig. 6. Areal mean summer maximum and minimum temperature and winter maximum and minimum temperature changes over the Yellow River basin

Figure 7 shows changes of days with summer mean maximum temperature exceeding 90th, 95th, and 99th percentile. Two periods, 1960–1984 and 1984–2004, can be identified, which are characterized by different changing patterns of fre-

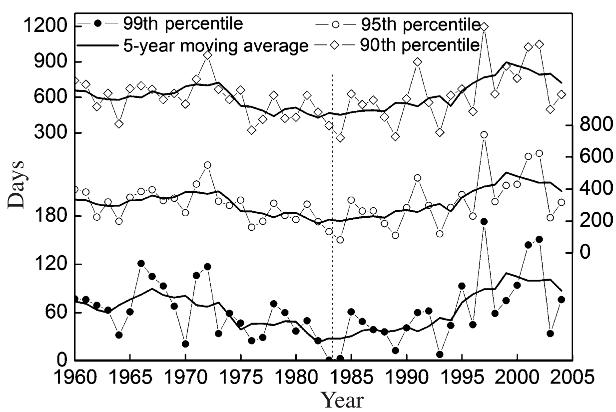

Fig. 7. Days with summer maximum temperature exceeding 90th, 95th, and 99th percentile

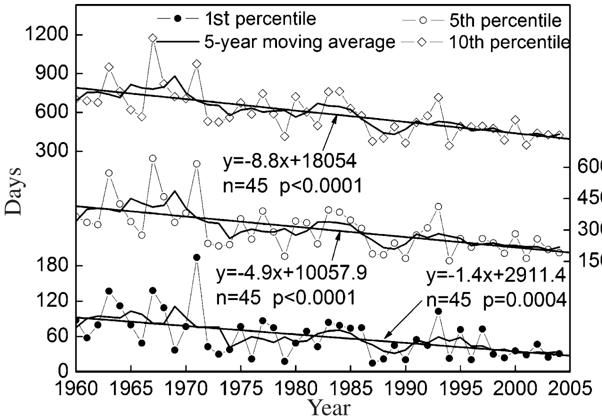

Fig. 8. Days with winter minimum temperature below 10th, 5th, and 1st percentile

quency of hot events. During 1960–1984, the frequency of hot events is decreasing, while after 1984, increasing frequency can be found. The increase is especially evident after early 1990s.

Figure 8 demonstrates the changes of days with winter minimum temperature falling below the 10th, 5th, and 1st percentile. It can be obviously seen from Fig. 8 that the areal frequency of the cold events over the Yellow River basin is decreasing for the whole study period. The curves of 5-year moving average show general decreasing trends. Simple linear regression analysis results indicate that these decreasing trends are all statistically significant at >95% confidence level.

4. Conclusion and discussion

In this paper, we analyzed the spatial and temporal patterns of the extreme winter and summer temperature based on the daily maximum and minimum temperature data set from 66 meteorological stations in the Yellow River basin with the help of Mann–Kendall trend test. Extreme hot events and cold events are defined by the seasonal maximum/minimum temperature and daily maximum/minimum temperature exceeding or falling below certain percentiles: 90th and 95th percentiles for hot events and 5th and 10th percentiles for cold events. The research results of the current study indicate that the Yellow River basin is in an obvious warming process, especially after 1980s. The warming trend over the Yellow River basin is described by the increasing frequency and intensity of hot events and decreasing frequency and intensity of cold events. The mean minimum temperature over days with daily minimum temperature falling below certain percentiles is decreasing significantly in most stations. Increase of daily minimum temperature in winter is more significant than that of daily maximum temperature in summer.

Generally, the west and north part of the Yellow River basin and also the lower Yellow River basin are more sensitive to climatic warming, and stations in these regions are characterized by significant increasing trend of hot events, decreasing trend of frequency of cold events and an increasing trend of minimum temperature in winter. Statistically significant warming trends at >95% confidence level were identified in various measures of the temperature regime. The warming trends in winter minimum temperatures were among the highest when compared with other extreme temperature events defined by various percentile thresholds. The stations in the west part of the Yellow River basin are characterized by a significant upward trend of frequency of extreme hot events and by a significant downward trend of frequency of extreme cold events. The west part of the Yellow River basin is the source for the water resources of the whole Yellow River basin. The evaporation in this region is sensitive to the increasing temperature. Increasing evaporation resulted from the warming trend in the upper Yellow River basin will offset the influences of precipitation on availability of water resources (e.g. Brutsaert 2006). During the past two decades, this region experiences a severer summer drought in spite of the fact that the annual precipitation remains unchanged or even increases in some places (Chen et al. 2005; Ren et al. 2005). More attention from the local government, the policy makers and the water resource management agency in the Yellow River basin, therefore, should be given to the future drought probably caused by the projected anthropogenic warming in this region (IPCC 2001; Ding et al. 2006). This conclusion should draw enough concerns from the local government, the policy makers and the fluvial management agency in the Yellow River basin.

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