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Changes in extreme daily mean temperatures in summer in eastern China during 1955–2000

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With 10 Figures

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Summary

Statistical characteristics of extremely low and high daily mean temperatures in summer (June, July and August) in eastern China have been investigated. The extremely low temperatures are defined as those days with temperatures not exceeding the 10th percentile with respect to the reference period of 1961–90; similarly the extremely high temperatures are defined as those exceeding the 90th percentile. There are well-defined spatial structures in trends of the frequency of extremely low temperatures as well as of high temperature extremes. In the north region (i.e. northern and northeastern China) the linear trends of frequency of low and high temperature extremes are -1.09 and $+1.23$ days/10 yr, respectively. For the southern portion of the study area, the trends are -1.32 and $+2.32$ days/10 yr. Taking the study area as a whole, the linear trends are -0.76 days/10 yr and $+1.08$ days/10 yr, respectively. The changes of frequency of extreme temperatures are mainly related to the shift in the temperature means. There is a dominant anticyclonic pattern in the lower- to middle troposphere over East Asia in association with warmer conditions in the north region. For the south region there is a jump-like change in the summer mean temperature and the extreme temperature events in around 1976. The large-scale northwestern Pacific subtropical high plays an important role in the jump-like changes of the temperature extremes.

1. Introduction

Changes in the frequency or intensity of extreme temperature events would have major impacts on society and the natural environment (Houghton et al., 2001). Karl et al. (1999) and Easterling et al. (2000) assessed changes in climate extremes over many countries. They reported a general reduction in the number of extremely cold days and an increase in extremely hot events. However, there are substantial regional variations in the trends, suggesting the complexity of the responsible mechanisms. To improve our understanding of the extreme temperature events in the context of global change, it is necessary to investigate their regional features and causes. Some simulation studies indicate that the greenhouse global warming would result in significant increase in extremely high temperatures in summer months over East Asia (e.g. Kharin and Zwiers, 2000; Gao et al., 2002). The analysis for the observation data sets would provide useful information for validating simulation results and understanding the responsible physical processes.

The target region of the present study is confined to eastern China (east of 95° E) where most of the country's population is concentrated. Both the high and low temperature extremes can cause considerable damages to agriculture. Successive hot days can cause and/or aggravate summer drought, particularly in the northern plains. Extremely low temperatures may result in heavy losses, too. For example, the gross agricultural production in northeastern China dropped by about 20–30% due to the extremely low temperatures in 1957, 1969, 1972 and 1976 (Ding, 1980; Sun et al., 1983). In terms of climate, the target region is also known as the East Asian monsoon region, where the strong summer monsoon dominates in warm seasons, which is often blamed for the numerous climate extremes (Huang and Zhou, 2002). Thus, it is of interest to address the possible association between temperature extremes and large-scale atmospheric circulation over East Asia. Recently more attention has been paid to the extreme temperature events over eastern China (for example, Zhai et al., 1999; Yan and Yang, 2000; Yan et al., 2001a, 2002). A few studies examined trends of summertime extreme temperatures. Some studies were concerned with changes in absolute daily maximum temperatures, say, those in excess of 35 °C (e.g. Zhai and Ren, 1997; Zhai et al., 1999). Few of those previous studies, however, analyzed the associated changes in the atmospheric circulation. In addition, it should be noted that those criteria of high extremes on the basis of absolute temperatures are much easier to be met in southern stations (south of about 30° N) than in the north. The absolute high temperatures are too strict for the high altitude stations. Probably, a more conservative and alternative method is to estimate the frequency of the highest and lowest temperature events with respect to the climatology for each station. That would be likely to eliminate the geographical and climatological difference among stations. In the present study we chose the 10th and the 90th percentiles as the thresholds to define the extremely low and extremely high temperature events, respectively. It is convenient to use this "popular" criterion to make the results comparable to other regions as well as to that by other authors.

Daily mean air temperature data sets and analysis method are presented in Section 2. Spatial features and the long-term variations in extremely low and high temperature events are presented in Section 3. The associations between the large-scale atmospheric circulation and temperature extremes are addressed in Section 4. Section 5 summarizes the results.

2. Data and method

2.1 Daily mean air temperature

Long time series of daily data are only available for a couple of stations such as Beijing and Shanghai since the late 19th century. The early data for these stations was reported containing inhomogeneities (Yan et al., 2001b). Vast portion of China has insufficient observations prior to the 1950s. The modern nation-wide networks of weather observing stations in mainland China began operation in the early 1950s. All daily mean air temperature data for eastern China used in the present study are obtained from the Chinese Meteorological Administration observation archives. In the target region (east of 95° E) there are 171 stations with data available since 1951. For many stations there are missing data in the early operating period from 1951 through 1954. Hence, our analysis period is confined to 1955–2000. Within this period, all stations with missing data for more than 3 days were excluded. Six stations with missing data less than three days were included. Finally, there are 145 stations retained, on which our analysis is performed.

As is known, a big problem in most stations with 'well-qualified' meteorological observations in China (as well as elsewhere) is associated with urbanization. A few studies estimated the influence of urbanization on the temperature observations (Wang et al., 1990; Zhao, 1991; Portman, 1993), however, none on the daily extremes. Obviously, it is a challenge to all researchers who use the daily data.

2.2 Quality control

Inhomogeneities in temperature records can be caused by a number of factors, including station location, instrumentation, observational practice, etc. Although a number of subjective or objective methods exist for identifying and adjusting monthly data (e.g. Easterling and Peterson, 1995), the condition for daily data becomes considerably complicated. These discontinuities will impact both the mean and the extremes. Given the fact that we focus on temperature extremes and that the outliers will evidently impact the results, we tested only for the outliers for simplicity.

In the present study we applied an objective method to identify any outliers for each station, every summer. According to the general weather knowledge, an extremely hot day may appear after a number of successive hot sunny days. The tendency to a climax is somewhat steady, that means the extremely high temperature should not appear abruptly, though the abrupt warming cases may occasionally be true at some mountain stations due to high Föhn wind. We see this as a minor problem, and just ignore that, since the Föhn wind seldom occurs over most portion of the study area in summer. Hence, we calculated the temperature difference between two consecutive days, i.e. $T_d' = T_d - T_{d-1}$, here T_d and T_{d-1} are the temperatures for days d and $d-1$, T_d' is the difference. If the rise in temperature (positive T_d') exceeds $+3.3\sigma$ (σ is the standard deviation of temperature difference series in a given summer), meaning an abnormal jump above the 99.9% possibility, the temperature record for day d was rejected. Extremely low temperature outliers were checked in a similar way, i.e., $T_d' = T_d - T_{d+1}$. Evidently, a temperature drop might actually be large in certain conditions. For example, heavy rainfall following consecutive sunny days may result in considerable temperature decline. However, when the rainfall stops, temperature would return to the before-drop level steadily. If there is an abnormally jump-back, the drop in temperature is rather suspect. Those temperature drops followed by a temperature jump-back beyond the 99.9% probabilities (i.e. $<-3.3\sigma$) are rejected. This procedure can be simply denoted as follows:

$$T_d' = T_d - T_{d-1}, T_d \text{ was rejected, if } T_d' > +3.3\sigma;$$

$$T_d' = T_d - T_{d+1}, T_d \text{ was rejected, if } T_d - T_{d-1} < 0 \text{ and } T_d' < -3.3\sigma.$$

In total there are 20 abnormally high or low records (about 0.003% of total record number) in 6 stations, they all are rejected according to the above criteria. It should be noted that this kind of testing does not identify any systematic errors or discontinuities, such as those resulting from the urbanization. Anyway, the removal of outliers would minimize the influence of possible data error on the analysis for extremes.

2.3 Method

Numerous extreme temperature indices have been used in previous studies. For example, Jones et al. (1999) chose the number of days with temperature above 20 °C to measure the hot days. This kind of index is only suited for the confined region with little spatial variability. For a region with large geographical extent, that is clearly inappropriate. Higher moments of climate variables are suggested to be usable for describing variability (Vinikov and Robock, 2002). For example, Gong and Ho (2003) used the skewness coefficient of daily temperature anomalies for depicting the wintertime cold surges and associated abnormal temperatures over East Asia. Indices based on statistical quantities such the 10th and the 90th percentiles are widely used (e.g. Jones et al., 1999; Plummer et al., 1999). Different thresholds, say the 1st, 5th, 95th, or 99th percentiles are used in some studies. It should be mentioned that these strict criteria could cause possible problems. Since the results would probably be sensitive to the outliers, the potential data errors may considerably change the frequency of extremes. Thus, in the present study we used the 10th and the 90th percentiles to define the extremely low and the extremely high temperatures, though this is a somewhat subjective choice. The 10th and the 90th percentile values are computed using all non-missing summer days (June 1 through August 31, 92 days in total each year) for the period 1961–1990. Then the frequency of extremely low temperatures was counted as the number of days with temperatures not exceeding the 10th percentile each year each station. Similarly, the frequency of extremely high temperatures was counted as the number of days with temperatures exceeding the 90th percentile.

3. Results

3.1 Spatial features in trends

After calculating the frequency of extremely low temperatures, we estimated their linear trends by using the ordinary least-squares technique fitting to entire data period. Figure 1 shows the results. Generally speaking, the tendency toward less frequency of low temperature extremes is dominant,

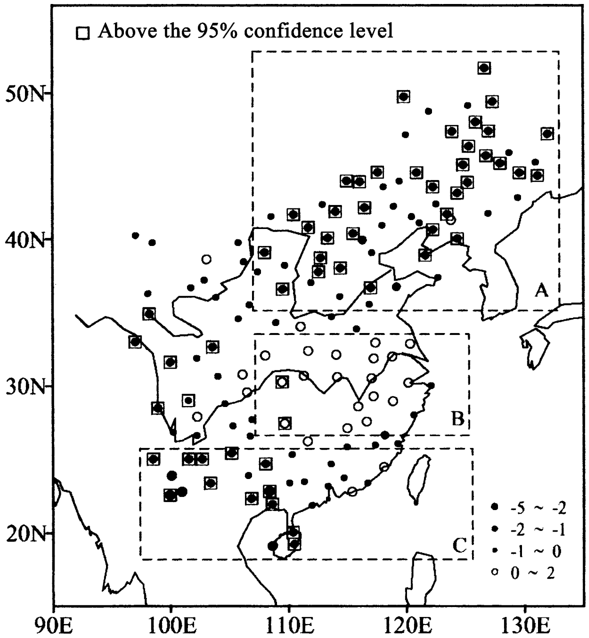

Fig. 1. Trends in the frequency of extremely low temperatures. Squares indicate stations with trends significant at the 95% confidence level. Values are shown in days/10 yr. Three rectangles with labels A to C indicate regions from which regional means are calculated

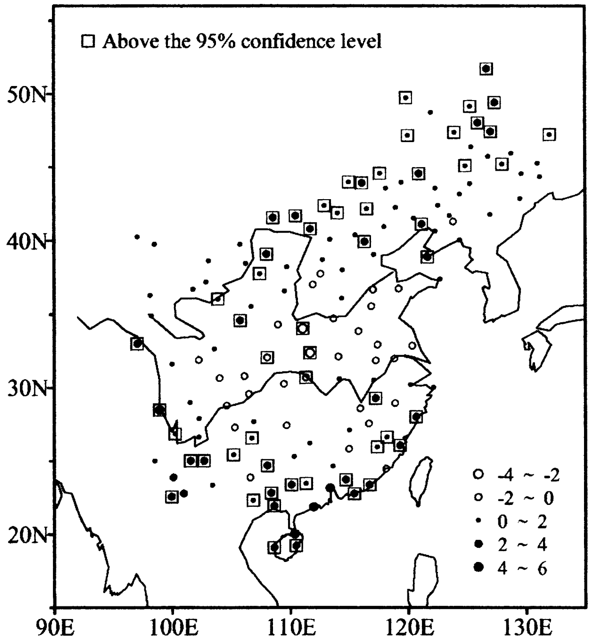

Fig. 2. Trends in the frequency of extremely high temperatures. Units are days/10 yr. Squares indicate stations with trends significant at the 95% confidence level

118 of the 145 stations being negative trend and only 27 stations showing positive values. Of importance is that these trends in extremely low temperatures show fairly well-defined geographical structure over the target region. Most stations with increasing tendencies are located in central China, i.e. along the Yangtze River valley, of which the trends are somewhat slight with values less than +1 day/10 yr. Whereas, the decreasing trends dominate other regions. The strong tendencies toward less frequency of low temperatures are clearly evident in northern and northeastern China, as well as in southern China, typical trends being in the range of -1--2 days/10 yr in both regions. This kind of north–south pattern is similar to the dominant patterns in other climate variables such as precipitation (e.g. Hu, 1997). Taking 145 stations as a whole, the trend is −0.76 days/10 yr, significant at the 99% confidence level. But as can be seen in Fig. 1 the differences amongst regions are remarkable, this might imply that there are different causes for each of these regions.

The distribution of trends in frequency of extremely high temperature events is shown in Fig. 2. These trends also exhibit geographical patterns similar to that in the low extremes, except for the opposite signs of change. For most stations along the Yangtze River valley, the frequency of the high temperatures decreases slightly with values lower than −2 days/10 yr. Two stations in this region are in the range of -4--2 days/10 yr. Contrast to the frequency of the extremely low temperatures, the positive trends in high temperatures are clearly dominant. Among the 145 stations, 113 experience increasing trends. Most significant stations are located in northern–northeastern and southern China. For 145 stations as a whole, the trend is −1.08 days/10 yr, significant at the 99% confidence level. The temporal features for these regions and the possible causes are discussed below.

3.2 Temporal variations

The apparently similar patterns in extremely high and low temperatures are of interest. The considerable geographical similarity of the trends exhibited in Figs. 1 and 2 encourage us to construct regional mean time series. In order to analyze the temporal features of temperature extremes and the possible reasons, three regions are selected as illustrated by rectangles A to C in

Fig. 1. They are: (A) the north region, i.e. northern and northeastern China, covering domain of 35–53° N and 107–135° E, including 62 stations, (B) the Yangtze River valley covering domain of 26.5–33.5° N and 107–123° E, 21 stations within it, and (C) the south region for domain of 17–26° N and 97–123° E with 28 stations situated there. Then we calculated regional mean time series by calculating simple arithmetic averages for each year.

3.2.1 North region

Figures 3 and 4 present the time series of the frequency of high and low temperature events, respectively. Clearly there are remarkable long-term trends in temperature extremes for this region. The trend for the low temperature frequency is −1.09 days/10 yr, statistically significant at the 99% confidence level. The trend for the frequency of high temperature events is even larger, +1.23 days/10 yr, significant at the 99% level too. This implies that in northern and northeastern China the frequency of high temperature extremes has increased by nearly six days, and the frequency of low extremes dropped by 5 days since the middle 1950s.

Other meteorological quantities in these regions have also been changing concurrently in a coherent way. Kaiser (1998; 2000) analyzed the cloud cover over China, and found there are decreasing cloudiness trends in much of the country. The largest decreases were observed in northern and northeastern China. From the early 1950s to the middle 1990s, the annual mean total cloud amount over these regions is as strong as −3%/10 yr in excess of 95% confidence level for many stations. The surface relative humidity over northeastern China was found to decrease simultaneously, with a rate of -1.0–-1.5%/10 yr. The number of rainy days in northern China has decreased by about 8 days since the middle 1950s, and furthermore the frequency of long duration dry spells (longer than 10 consecutive days without rainfall) has been increasing at a rate of +7.2% per 10 yr (Gong et al., 2003). Dry spells are obviously related to the high temperatures. The more frequent and the longer the dry spells are, the more the high temperature extremes get. These changes in cloud, relative humid, rainy days, and dry spell duration all are evidently in good agreement with the changes in extreme daily temperatures over the north region.

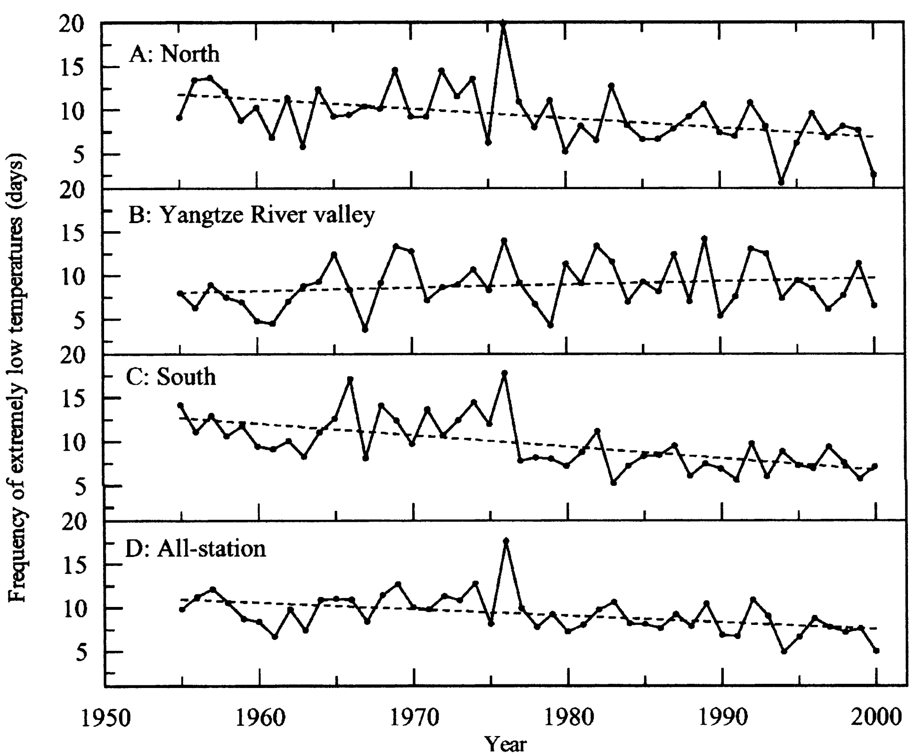

Fig. 3. Time series of regional mean frequency of extremely low temperature events. Three regions are indicated as rectangles in Fig. 1. An all-station series is also shown for comparison. Dashed lines superimposed on the time series are the linear trends estimated using the least-squares method

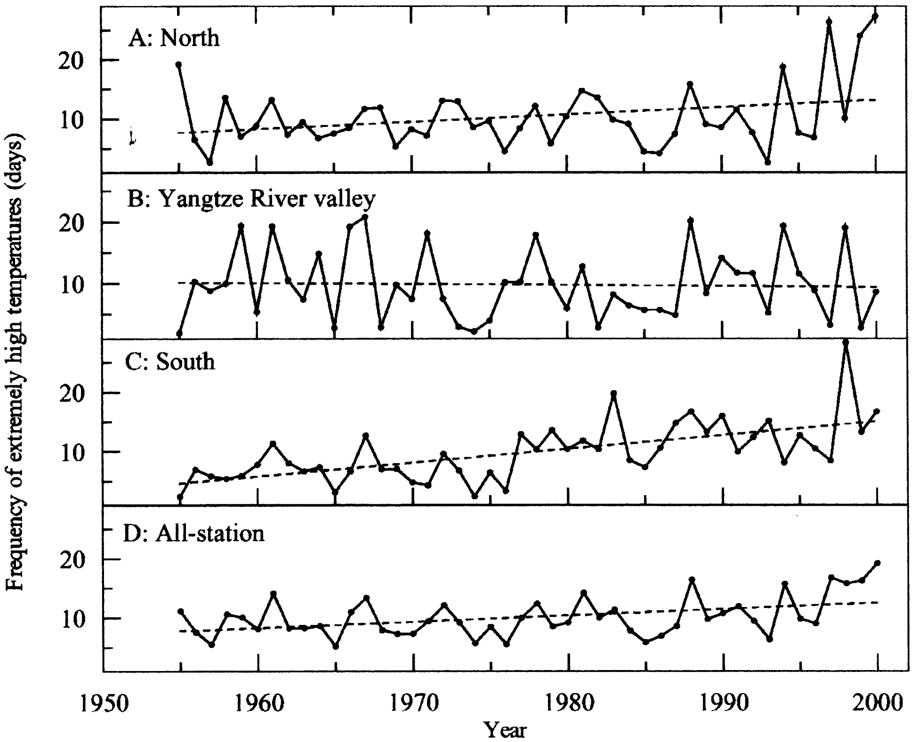

Fig. 4. Same as in Fig. 3, but for the extremely high temperature events

3.2.2 The Yangtze River valley

Unlike the northern region, the Yangtze River valley does not display evident secular change in both the low and high temperatures. Linear trends are +0.37 and −0.16 days/10 yr, respectively, neither statistically significant. The concurrent mean temperature shows a slight decreasing tendency. That might be related to the precipitation increase there. Previous studies reported that the summer precipitation across the *Meiyu* belt (along the Yangtze River valley) has notably increased, in particular since the 1980s (Gong and Ho, 2002; Gong et al., 2000). The increasing precipitation amount and rainy days would result in a cooler tendency in the mean temperature, giving rise to more occurrence of the low temperature events and less occurrence of the high temperatures, though these changes are not as great as, nor as significant as those in the north and south regions.

3.2.3 South region

Among all three regions, the south region experiences the largest linear trends in both the low and high extremes. The trend for the low temperature frequency is −1.32 days/10 yr, statistically significant at the 99% confidence level. The trend for the high temperatures is +2.32 days/10 yr, the largest of all the extreme trends as listed in Table 1. It is interesting to note that the summer temperature extremes in the neighborhood show comparable trends. For example, Manton et al. (2001) analyzed the changes in hot days, as well as the cool days across Southeast Asia and the

Table 1. Trends in the frequency of extremely low and high temperatures for various regions

	Frequency of low temperatures (days/10 yr)	Frequency of high temperatures (days/10 yr)	Mean temperature (°C/10 yr)
North region	−1.09**	1.23*	0.19**
Yangtze River valley	0.37	−0.16	−0.08
South region	−1.32**	2.32**	0.14**
All-station	−0.76**	1.08**	0.11**

* Significant at the 95% confidence level, those with ** at 99%

South Pacific. They defined the hot days as days with maximum temperature above the 1961–1990 mean 99th percentile, cool days as days with maximum temperature below the 1st percentile. They found that the number of hot days has increased at most stations over the adjacent Southeast Asia (including Vietnam, Thailand, Philippines, Myanmar, etc), simultaneously, the cool days have declined in frequency. These are consistent with our results for southern China. Clearly, the changes in summer mean temperature and extremes are of large-scale, covering considerably broad geographical extent. In the next section we will show that this is closely related to the variations in northwestern Pacific subtropical high.

3.3 About the mean and the frequency of extreme events

The daily temperatures for a location often tend to obey the normal distribution. Changes in both mean and variance can notably affect the occurrences of the extreme temperatures. If the mean shifts to the warmer side, more extremely high and less low temperatures would be expected. And, less variance means less frequency in both low and high temperatures (e.g. Katze and Brown, 1992; Houghton et al., 2001). The importance of the combination influence of the mean and the variance on the probability of extreme events was also emphasized recently. A rise in the mean accompanied by an increase in the variance can lead to a remarkable rise in the frequency of extremely high temperatures. Contrast to that, a rise in the mean accompanied by a decrease in the variance may result in decrease in the high temperatures (Robeson, 2002). It is of interest to analyze the dependence of extreme daily temperature events in China on the changes in the mean, the variance or their combination.

We compared the temporal behavior of the variance to those of the temperature means, the low and high temperature extremes by calculating the correlation coefficients between them. A high pass filter (retaining only components shorter than 20 days) is applied to the daily temperatures prior to the analysis, which served to remove the influence of seasonal cycle on the variance and put the emphasis on the day-to-day variability within each summer. We found that there are no dominant trends in the day-to-day variance in most stations, nor for the regional average series. We calculated the correlation between the time series of the means and the frequency in extremes. Contrary to variance, there are overall tight and significant relations. The mean temperatures show remarkable trends as well, which are comparable to the changes in the low and the high extremes in both the spatial and the temporal features. As can be seen in Fig. 5, the spatial pattern of trends in mean temperature is nearly identical to those in the low and high extremes. The mean summer temperature over the northern region, on average, shows a large upward trend at the value of 0.19 °C/10 yr, for the southern region the change rate is 0.14 °C/10 yr, both statistically significant at the 99% confidence level. The temporal variations also agree well with the yearly changes in the frequency of extremes as indicated by the high correlations between them. The mean temperature of the northern region correlates with the low and the high extremes there at −0.77 and 0.89, respectively. For the southern region, the correlations are −0.89 and 0.91, respectively. All suggest a tight relationship between the means and the frequency of the extremes.

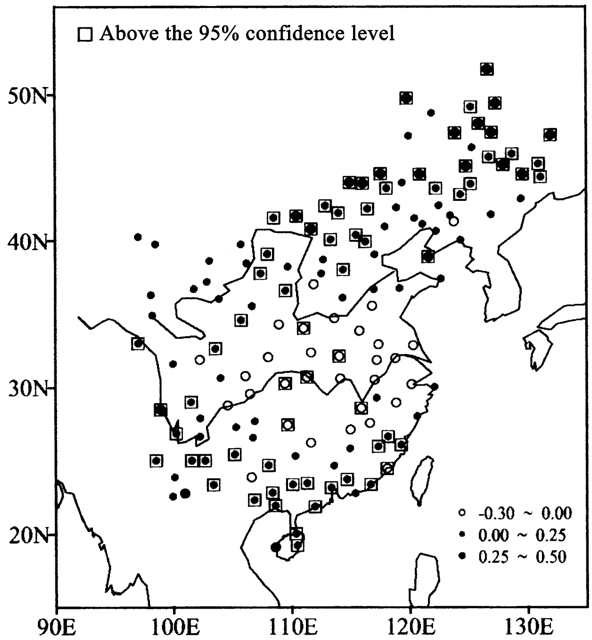

Fig. 5. Trends in the summer mean temperature. Units are degrees Celsius/10 yr. Squares indicate stations with trends significant at the 95% confidence level

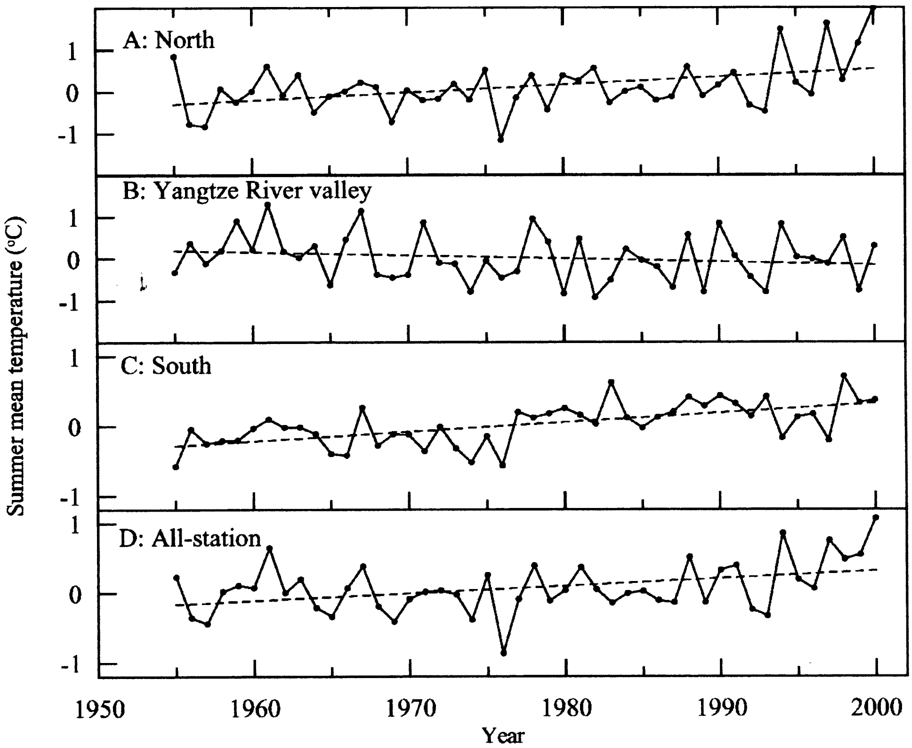

Fig. 6. Time series of regional mean summer temperature anomalies with respect to 1961–1990. Please note that the vertical axis scales are different for clear comparison

It is interesting to note that the frequency of extremely high temperatures shows much larger trends than the extremely low temperatures in the northern region as well as in southern China, implying that the changes in high and low temperatures are somewhat asymmetric. This is likely to be related to the asymmetric responses of probability density function (PDF) of daily temperatures to the changes in temperature means, i.e. a shift to a warmer mean could result in a greater change in the high end than in the low end. As a schematic illustration shown in Fig. 7, for a normal distribution temperatures with a zero mean and a one standard deviation, a 0.5 °C rise in the mean will result in changes in two sides of the PDF. Importantly, the changes in the positive and the negative sides are uneven. If defining the high and low extreme temperatures as the upper and lower 10% probabilities, a +0.5 °C shift toward the positive side would cause the frequency in high extremes to increase by 11.7%, whereas the frequency in the low end drops only by 6.3%. The larger the shift is, the greater the asymmetry will be. Therefore, from our analysis the conclusion can be derived that the changes in the frequency of extreme temperature events in eastern China are mostly related to the changes in the temperature means. The changes in the variance and their impacts on the PDF are not evident.

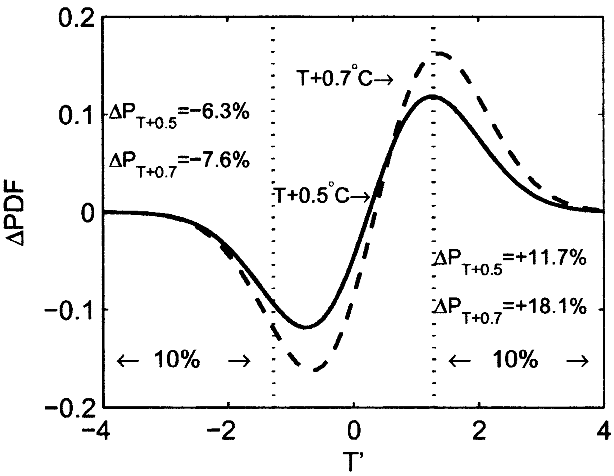

Fig. 7. Schematic illustration of probability density function (PDF) changes due to a shift of the mean. Shown here are two examples, one for the mean temperature rise of 0.5 °C, and the other of 0.7 °C. The probabilities in high- and low-end extremes will be considerably unequal in association with the shift

4. Associated large-scale atmospheric circulation pattern

The immediate cause for a specific extreme temperature event is a conductive synoptic situation.

However, the monthly to seasonal mean circulation anomalies would provide the dynamic background for the varying mean temperature and daily extreme events. Instead of studying high frequency daily transient circulation changes, we investigate the large-scale atmospheric circulation patterns related to the variations in regional mean temperatures on the monthly-seasonal time scales. That, alternatively, would be served to give helpful information for better understanding the spatial-temporal features in the temperature extremes, since the significant changes in the north and south regions are tightly associated with the monthly-seasonal means as the above analysis shows. In this section we focus on only these two regions, i.e. the northern region and the southern region where significant secular changes in both temperature mean and extremes are observed.

4.1 North region

To investigate the favorable atmospheric circulation patterns for temperature variations, we regressed the regional mean temperature upon the 500 hPa height anomalies and 850 hPa wind vectors over East Asia. Here the atmospheric circulation data are taken from the National Centers for Environmental Prediction/the National Center for Atmospheric Research (NCEP/NCAR) reanalysis data set (Kalnay et al., 1996). To facilitate comparison, all height and wind data are adjusted to the period 1955–2000 as the same time span of temperature data. Figure 8 displays the changes of 500 hPa height and the 850 hPa wind velocity in association with a one standard deviation anomaly in temperature. The major feature is that there is an anomalous large-scale anticyclonic pattern with a center situated over northern East Asia. The similar pattern is also evident at the lower level as the 850 hPa wind velocity anomaly suggested. The anomalous center covers a broad extent of area, from Mongolia to the north Korean Peninsula and northern Japan. Some previous studies have reported that in these regions the temperature changes, to a greater degree, in a consistent way as the empirical orthogonal function analysis revealed. That is true for both the summer mean temperature and the temperature extremes (Wang, 1990).

4.2 South region

Figure 9 presents the atmospheric circulation changes in association with the anomaly in mean temperature of the southern region. In the condition when summer mean temperature getting one standard deviation warmer, the 500 hPa geopotential heights are anomalously high at two centers. One center is located over southern China

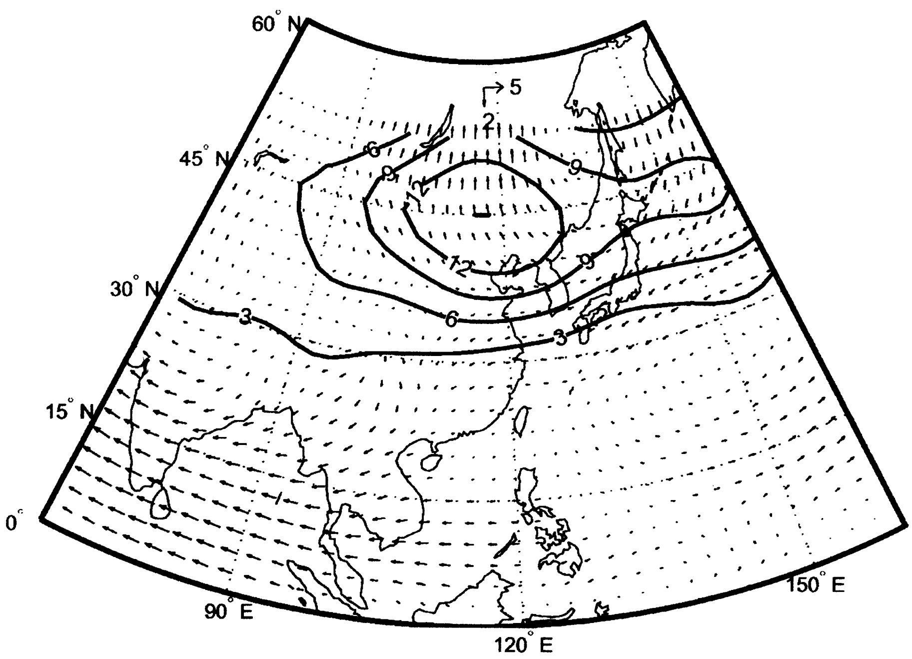

Fig. 8. Changes in 500 hPa height (contours, in gpm) and 850 hPa wind velocity (vectors, in ms^{-1}) in association with a one standard deviation anomaly in mean temperature of the north region. Height and wind data are taken from NCEP/ NCAR reanalysis data sets for period 1955–2000

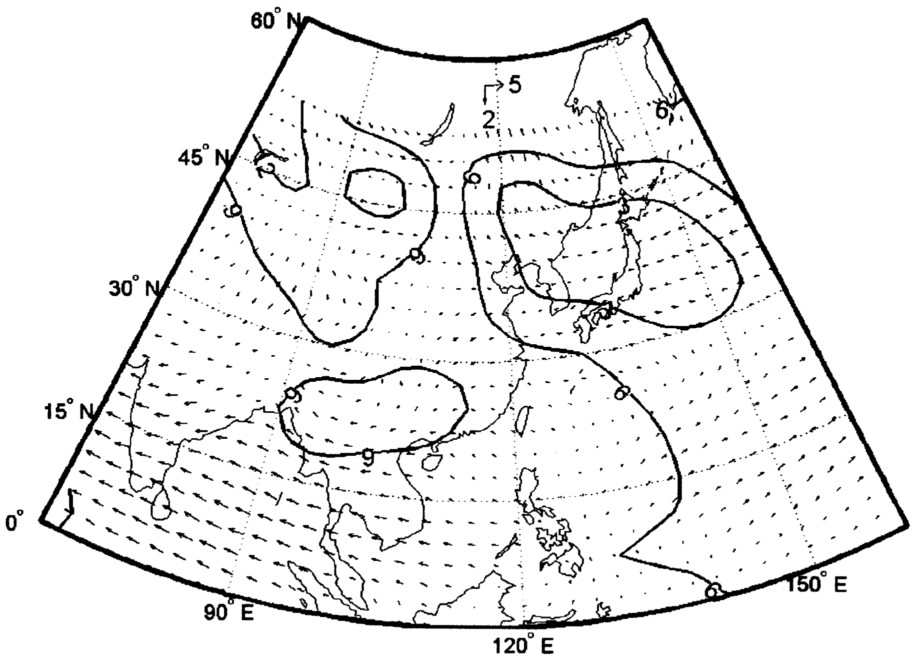

Fig. 9. Changes in 500 hPa height (contours, in gpm) and 850 hPa wind velocity (vectors, in ms^{-1}) in association with a one standard deviation anomaly in mean temperature of the south region. Data period is 1955–2000

and the neighboring regions to the west, and the other is located around Mongolia. The southern center is of most interest since the west–east-directed area with high regression coefficient covers aloft the southern China, where great changes in mean temperature and extremes occur. This pattern exists at the 850 hPa level too. Both 500 hPa height and 850 hPa wind display similar anticyclonic patterns in there and the vicinity. This anomalous center would be strongly related to the northwestern Pacific subtropical high (NPSH), which is the most important circulation system dominating the lower to middle troposphere circulation over the western

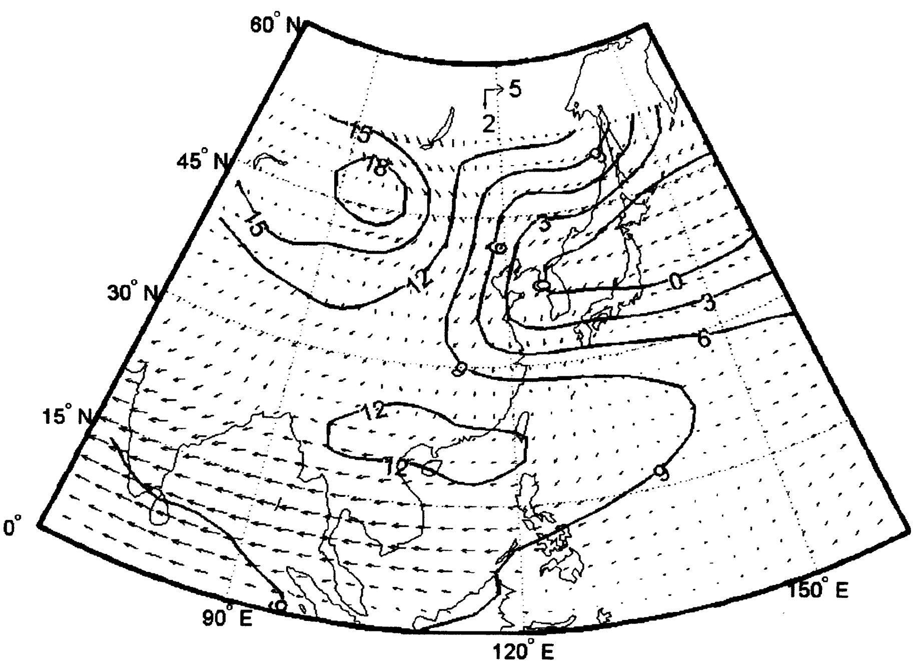

Fig. 10. Changes in 500 hPa height (contours, in gpm) and 850 hPa wind velocity (vectors, in ms^{-1}) in association with a one standard deviation anomaly in western north Pacific subtropical high index. NCEP/NCAR reanalysis data, 1955–2000

Pacific and lower- to middle latitudes East Asia (Zhang and Lin, 1992). To quantitatively assess the influence of the NPSH on the circulation and temperature over southern China, an index for the subtropical high is used here, that is defined as the mean 500 hPa height averaged over the domain 20–25° N, 125–140° E. This region is, in climatology, located at the western flank of the northwestern Pacific subtropical high. The pressure there is sensitive to the strength and location of the NPSH (Gong and Ho, 2002). We calculated the related changes in 500 hPa and 850 hPa wind, by regressing them onto the normalized subtropical high index. The results are displayed in Fig. 10. Comparison of Figs. 9 and 10 show there are considerable similarities. The centers and their locations are nearly identical. The positive center in southern China and the vicinity is of most importance. Clearly, when the subtropical high gets stronger and extends westwards, there will be evident positive 500 hPa height anomalies, and an enhanced downward air motion in association with the subtropical high, consequently resulting in higher temperature and more high temperature extremes in southern China and the vicinity such as Southeast Asia (Manton et al., 2001).

Since the NPSH is regarded as one of the essential components of the East Asian summer monsoon, in order to check whether the subtropical high might exert influence on summer climate, we calculated the correlation between the subtropical high and the temperatures in other regions. As Table 2 illustrated, a significant relationship exists only in southern China. This may be due to the fact that the subtropical high exerts influence on the south region's temperature in a direct manner, but for the other regions its influence is mostly indirect. Hence it is not likely to have an overall tight linkage between the subtropical high and the temperatures over the whole of eastern China, though the subtropical high influences surface climates in vast regions over East Asia.

Table 2. Correlation between the northwestern Pacific subtropical high index and the frequency of extreme temperatures for various regions

	Frequency of low extremes	Frequency of high extremes	Mean temperature
North region	−0.25	−0.02	0.07
Yangtze River valley	0.26	0.02	−0.26
South region	−0.51*	0.66*	0.62*
All-station mean	−0.28	0.19	0.09

* Significant at the 99% confidence level

Table 3. The t-test for the temperature mean and extremes in southern China

	Mean for 1955–1976	Mean for 1977–2000	t-value
Summer mean temperature	−0.20 °C	0.22 °C	6.6*
Frequency of low extremes	12.0 days	7.7 days	7.1*
Frequency of high extremes	6.5 days	13.0 days	6.0*
Northwestern Pacific subtropical high	5862.1 gpm	5876.3 gpm	6.1*

* Significant at the 99% confidence level

It is interesting to note that there are decadal time scale jump-like changes in the mean temperature and frequencies of extremes in south region. Table 3 summarizes the t-test for the jumps. The changes in mean and extremes are all statistically significant at the 99% confidence level. Gong and Ho (2002) reported that there is a similar decadal change in the northwestern Pacific subtropical high during the late 1970s. However, it should be mentioned that the exact time is slightly different. For the temperature the most significant changes occurred in around 1976, and for the subtropical high in about 1979. Despite of that, the t-test for the subtropical high also shows a significant difference in 1976. Therefore, the changes in temperature are generally in good agreement with the decadal time scale strengthening of the northwestern Pacific subtropical high during the late 1970s. The subtropical high is able to account for a large portion of the variance in temperature on decadal time scale at a value of 66.3%.

5. Conclusion and discussion

The spatial pattern of linear trends in extremely low temperatures exhibits well-defined structures across the target region. In the Yangtze River valley, the positive trend dominates, while the tendency toward less low temperatures is profound over the other regions. The same is true for the trends in the frequency of extremely high temperatures, except for the reversal signs of change.

Statistically significant secular changes are found in the north region as well as in the south region. In the north region, the linear trends in low and high temperature extremes are -1.09 and $+1.23$ days/10 yr, respectively. Those in the south are -1.32 and $+2.32$ days/10 yr. Averaged over eastern China (145 stations), there is a significant decreasing trend of -0.76 days/10 yr in the frequency of low extremes, and a significant increasing trend of $+1.08$ days/10 yr in the frequency of high extremes. The frequency changes in the extremes are mainly related to the shift in the means, whereas no evident association is found between the day-to-day variance and the extremes.

The major feature of temperature extremes as exhibited in the present study are, to a certain degree, similar to those previous findings for the absolute minimum and maximum temperatures (c.f. Zhai and Ren, 1997; Ren and Zhai, 1998; Zhai et al., 1999; Yan and Yang, 2000). As those studies revealed, the maximum temperatures over eastern China are generally decreasing with the greatest values located along the Yangtze River valley at the rate of -0.3–-0.7 °C/10 yr. A small region near the southern coast shows increasing trends. Meanwhile, the minimum temperatures are getting slightly higher for most stations in northern and southern China, and getting cooler at some stations along the Yangtze River valley. Conditions in the southern region and the Yangtze River valley are clearly consistent between these studies, though different research approaches are employed. However, the trends of maximum temperatures over the northern region as estimated in our results and in previous studies are apparently contradictory. One possible reason may be the difference of data periods. Those previous studies covered periods prior to the middle 1990s. Here our data period is updated to the year 2000. As shown in Fig. 4, in recent years there were very high frequencies of high extremes, the trends would be greatly reduced if these years were excluded.

In addition, our results are consistent with the concurrent changes in the large-scale atmospheric circulation. The anticyclonic pattern is predominant in the 500 hPa geopotential height as well as in the 850 hPa wind velocity field over East Asia in association with a warmer condition of the northern region. The anomalous center covers a broad extent of area from Mongolia to northern Japan. In southern China the large-scale northwestern Pacific subtropical high plays a very important role in the varying temperatures. In 1976 a jump-like change in the mean temperature was experienced as well as in the extreme temperature events. That is in good agreement with the decadal changes in the subtropical high.

The subtropical high may play an important role for the temperature extremes over Yangtze River valley. Cool days are usually directly caused by heavy rains. The remarkable increasing trend in summer precipitation along the Yangtze River valley is particularly interesting. Mean summer precipitation there is significantly (at the 99% confidence level) correlated with the subtropical high at a value of 0.50 (Gong et al., 2000; Gong and He, 2002). Therefore the subtropical high may exert substantial influence on low temperature extremes by impacting precipitation. Of course, besides the subtropical high, some large-scale anomalous patterns in middle latitude circulation might be, at least partly, responsible for the jump-like changes in the 1970s (e.g. Ho et al., 2003), though their possible influence on temperature extremes needs further investigation.

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