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Regional trends in recent temperature indices in China

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ABSTRACT: Regional trends in recent temperature indices in China were analyzed from daily surface air temperature maxima and minima at about 498 stations during 1961 to 2000. Some indices based on percentile and those modified by previous studies were used, and linear trends were analyzed for different regions in this study. Results show significant changes in important temperature indices over the past 40 yr, especially in northern China, the Yangtze River valleys and Xinjiang. Trends of decreasing diurnal temperature range were found in mainland China as a whole during 1961 to 2000, with stronger decreases in Northeast China, central South China and the Xinjiang region. There is a trend of cool days significantly decreasing in the middle latitudes near 40° N along the Yellow River valley. There are trends of increasing warm days in the upper-middle Yellow River valley and other regions such as along the coast of South China, while there are decreasing trends scattered in the central part of East China. The number of frost days decreased significantly in most of mainland China. Consecutive warm days significantly increased in northern China, while consecutive cold days decreased largely in Xinjiang, the Yellow River valley, the southern part of northeast China, and along the southeast coast of the country. In examining the seasonal contribution, cool nights largely decreased in winter as a whole and the linear trend is about –2.5 to –5 d/10 yr. Another contribution of cool nights comes from summer except for the region of the mid-low Yangtze River valley. The contribution of warm days is attributed to the higher temperature in winter over northern China and in summer over western China and along the coast of South China but a decreasing trend is noted in the basins of the Yangtze and Huaihe Rivers. These trends of temperature indices may be caused by climate factors, such as more rainfall in the Yangtze River basin and dry climate along the Yellow River valley, and non-climate factors, such as urbanization and industrial aerosols.

KEY WORDS: Temperature indices · China · Regional climate trends

1. INTRODUCTION

Climate conditions such as consecutive warm days and consecutive cold days can have important impacts on human society, the economy and the environment. Karl et al. (1999) assessed changes in climate extremes over many parts of the world during the past century. Frich et al. (2002) calculated changes in climate extremes in the land areas of North America, Eurasia and Australia during the second half of the 20th century. They reported a reduction in the number of extremely cold days, including reduced frosts, in China, and an increase in the number of extremely hot days in northern China but a decrease in the number of extremely hot days in South China. In China as a whole, changes in the trends of some extreme temperature events—the number of hot days ($T_{\max}$ >35°C) and frost days ($T_{\min}$ <0°C) as well as warm (cool) days and warm (cool) nights—were studied by Zhai & Pan (2003) by examining the data of about 200 stations during 1951 to 1999. Changes in temperature and precipitation extremes have also been studied by using observational data after 1950 for China as a whole (Zhai et al. 1999). Several of the longest (about 100 yr)

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daily temperature series available in China have been analyzed and results show that the annual frequency of cold extremes has decreased by about 7% per century, with a warm extreme increasing by more than 10% per century but with large spatial variability (Yan et al. 2002).

The global average surface temperature increased over the 20th century by about 0.6°C and there is evidence that the warming of the latter half of the 20th century was due primarily to human activities (IPCC 2001); however, the mean annual temperatures over northwestern North America rose 1 to 2°C in the same period (Hansen et al. 1999, Cayan et al. 2001). This is evidence that the climate changes in various regions are different. For decision makers in a country or a region, it is insufficient for them to merely know the average climate change. Studies of extreme events in South Korea also indicate some difference from the global trend; for example, an upward trend of daily temperature range is caused by a faster increase of maximum temperature (Jung et al. 2002).

China is strongly influenced by the East Asian monsoon (Qian & Zhu 2001). During the winter half year, the climate is mostly cold and dry. Cold days and strong winds accompanied by dust storms are the major climate features particularly observed in northern China (Qian et al. 2002a). During the summer period, the rain belt moves gradually from south to north with the hot and humid climate in eastern China (Qian et al. 2002b). The regional characteristics of climate are particularly prominent in China.

In order to reveal in detail the regional characteristics of extreme temperature indices in China, the daily temperatures based on about 498 stations during 1961 to 2000 are used in this paper. Quality controls and the method of analysis are described in Sections 2 and 3. The regional characteristics of upper and lower temperature indices are shown in Section 4. Discussion and a summary are given in Sections 5 and 6.

2. QUALITY CONTROL

Climatic data are essential to our effort to identify and understand variations and changes of regional and global climate. Recently, a global daily meteorological dataset was developed at the U.S. National Climatic Data Center (NCDC) (Gleason 2002). This global daily meteorological dataset includes surface air temperature and precipitation data from 1951 to the 1990s at 196 stations in China (Gleason 2002). In fact, 196 stations may be the maximum number during the first decade of the 1950s so that many studies have used only the data from 160 stations since 1951. This number is a small portion of the total number (726) of stations in China after 1960. In addition, most of those stations have recorded measurements of other important meteorological variables, such as daily mean skin surface temperature (*Ts*), relative humidity (*RH*), wind speed (*Ws*), wind gusts (*Wg*), sunshine duration hours (*SS*), and pan evaporation (*PE*).

Daily observations from 726 stations (Fig. 1) were obtained from the Chinese National Meteorological Center (CNMC). These data are observations of 10 variables: daily maximum surface air temperature (*Tx*), daily minimum surface air temperature (*Tn*), daily mean surface air temperature (*Td*), daily total precipitation (*Pr*), and the variables previously mentioned: *Ts*, *RH*, *Ws*, *Wg*, *SS*, and *PE*. Peterson (2003) described a rather bewildering variety of instruments in use in the USA. The standards of the measurement instruments in China have been outlined in Tao et al. (1991) and Kaiser et al. (1993). No changes ever occurred in these measurements from 1951 to 2000 except for the PE sensors in mainland China. The stations are fairly evenly distributed in the plains east of 95° E longitude. A large void exists in the western Tibetan Plateau and the Tarim basin in Xinjiang Province. Although the number of stations in service has changed over the years, the total number of stations that measure *Td*, *Tx*, *Tn*, *Ts*, *Ss*, *Ws* and *Pr* has remained at about 660 since the network was established around 1958. In the early 1950s, the number of temperature observational stations ranged from about 160 to 400.

The method of quality control (QC) is based on the daily values of temperature and precipitation from individual stations with established extreme values. The temperature extremes defined by Gleason (2002) are used to check the stations' daily temperatures. A detailed description of the QC can be noted from our recent work (Feng et al. 2004) and from Pan & Zhai (2002). The QC includes examining the internal and spatial consistency between the daily mean, maximum and minimum temperatures. To minimize the influences associated with temporal inhomogeneity, stations with serious relocation events, and data records with erroneous types and incorrect units, readings, or data coding were removed. The sources causing the spatial inconsistencies/discontinuities, such as those stations with unusual altitudes compared to the neighboring stations (e.g. the station of Taishan which is located on the highest mountain of the Shangdong plains), were removed.

After the steps mentioned above, possible sources which may cause error were eliminated and some scattered missing data were filled in, but continuous missing data as well as urbanization influences still exist. Some other steps were taken as follows: (1) omit stations with long consecutive missing data (>8 d) or too much missing data in total (>30 d), (2) omit stations

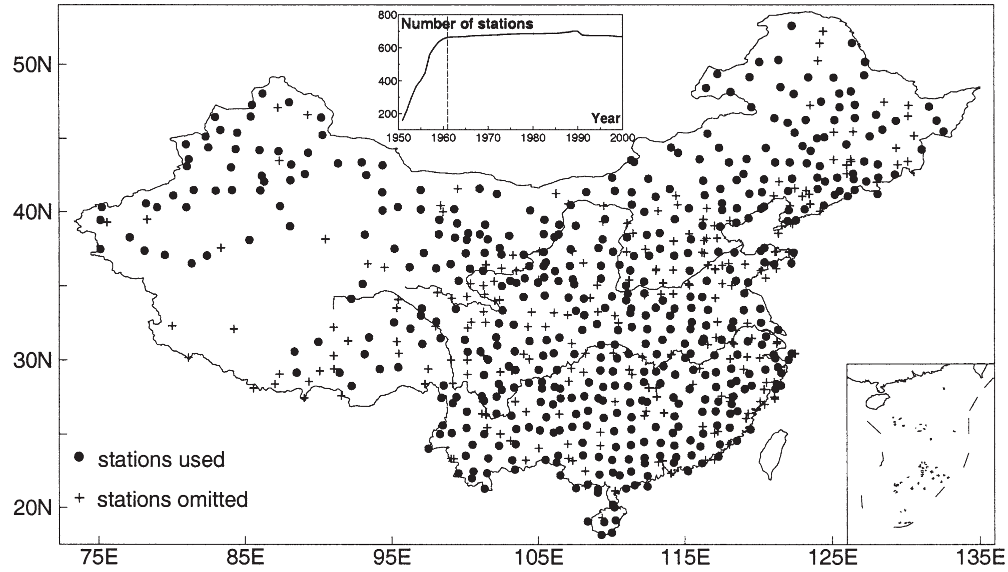


Fig. 1. Stations for which data were available in China. (●) Stations used in this paper; (+) stations omitted due to quality control. The upper small figure indicates the total number of stations from 1951 to 2000

experiencing relocation, and (3) omit stations in cities with populations above 0.5 million. In total, stations near 56 big cities were removed.

Data remained for a set of 498 high-quality stations (Fig. 1) from 1961 to 2000 based on the above testing and QC. Few stations remained in the middle and western Tibetan Plateau, so we only mention East Tibet in the study.

3. METHOD OF ANALYSIS

Numerous temperature indices have been used in previous studies of climate events. Some indices involved arbitrary thresholds, such as the number of hot days exceeding 35°C and summer days exceeding 25°C. As indicated by Monton et al. (2001), these are suitable for regions with little spatial variability in climate, but arbitrary thresholds are inappropriate for regions spanning a broad range of climates. In China, climates vary widely from the monsoon region in the eastern part to the westerly region in the northwestern part of the country, so there is no single temperature threshold that would be considered events in all regions. For this reason, some studies have used weather and climate indices based on statistical quantities such as the 10th (5th) or 90th (95th) percentile (Plummer et al. 1999, Peterson et al. 2002); detailed information can be found from the European Climate Assessment & Dataset (EC&D) Indices List (www.knmi.nl/samenw/eca). Upper and lower percentiles of temperature indices are used in all regions, but vary in absolute magnitude from site to site. A regional climate study in the Caribbean region using the same indices can also be found in Peterson et al. (2002).

As this study covers a broad region in China, climate indices chosen are based on the 10th and 90th percentiles as well as some fixed thresholds for the daily temperature. Fixed thresholds are taken only where they can be used for any site. A least squares approach for calculating the linear trend and Kendall's tau significance test (Kendall & Gibbons 1981) for series with the statistical Gaussian distribution were used. For this paper we chose the temperature indices as given in Table 1.

4. TRENDS IN UPPER AND LOWER TEMPERATURE INDICES

In this section, a total of 11 temperature indices and their trends are considered. Fig. 2 shows the spatial distribution of trends for the diurnal temperature range (DTR) in China during 1961 to 2000. Decreasing trends of the DTR can be observed in mainland China as a whole, and the most significant trends are located in Northeast China, central South China and Xinjiang (far Northwest China). The temporal time courses of the DTRs in these regions are given in Fig. 3; the strongest decrease occurred in Northeast China. All 3 of the chosen regions had their highest DTR during the first half of the 1960s, and these decreased significantly to their lowest DTR in the middle of the 1980s, but the Xinjiang DTR reached a maximum in 1997 after a long period of decrease while in the other 2 regions no such re-increasing trend can be found. Decreasing trends of the DTR in Northeast China and Xinjiang are about 1 to 1.25°C in the last 40 yr with slopes of −0.033 and −0.026°C/yr, respectively. In South China, the slope is −0.017°C/yr. The greatest contribution to the annual trend was found in the winter season (DJF) in these 3 regions, but in Northeast China, the trend of autumn (SON) is larger than both the spring (MAM) and summer (JJA) ones. Details on the seasonal trends can be found in Table 2. Increasing trends occur in the middle valley of the Yellow River but few stations reach the significance level. Along the coast there are also several stations with increasing trends of DTR. Decreasing trends of DTR in China are consistent with the results of Frich et al. (2002).

Table 1. Temperature indices

Category	Index	Description
1 Temperature range	DTR	Diurnal temperature range
	GSL[a]	Growing seasonal length
2 Cold temperature percentiles	Tx10p	Days with $Tx < $ 10th percentile of daily max. temp. (cold day-times)
	Tn10p	Days with $Tn < $ 10th percentile of daily min. temp. (cold nights)
	CCDI[b]	Consecutive cold day index
3 Warm temperature percentiles	Tx90p	Days with $Tx > $ 90th percentile of daily max. temp. (warm day-times)
	Tn90p	Days with $Tn > $ 90th percentile of daily min. temp. (warm nights)
	CWDI[c]	Consecutive warm day index
4 Cold temperature fixed thresholds	Fd	Frost days ($Tn < 0°C$)
	Id	Ice days ($Tx < 0°C$)
	FSL	Frost seasonal length (days from the first $T_n < 0°C$ to the last $T_n < 0°C$)

[a] GSL: number of days starting from the first day to the last day with the occurrence of at least 6 consecutive days with $Td \geq 5°C$

[b] CCDI: let $T_{i,j}$ be the daily minimum temperature at Day i of Year j and let $T_{i,\mathrm{mean}}$ be the mean of Day i calculated for a 5 d window centered on each calendar day where the temperature of the calendar day is the mean of 1961 to 1990. Then CCDI is the number of days per period where, in intervals of at least 6 consecutive days, $T_{i,j} < T_{i,\mathrm{mean}} - 5°C$

[c] CWDI: same as CCDI but for $T_{i,j} > T_{i,\mathrm{mean}} + 5°C$, and $T_{i,j}$ is daily maximum temperature

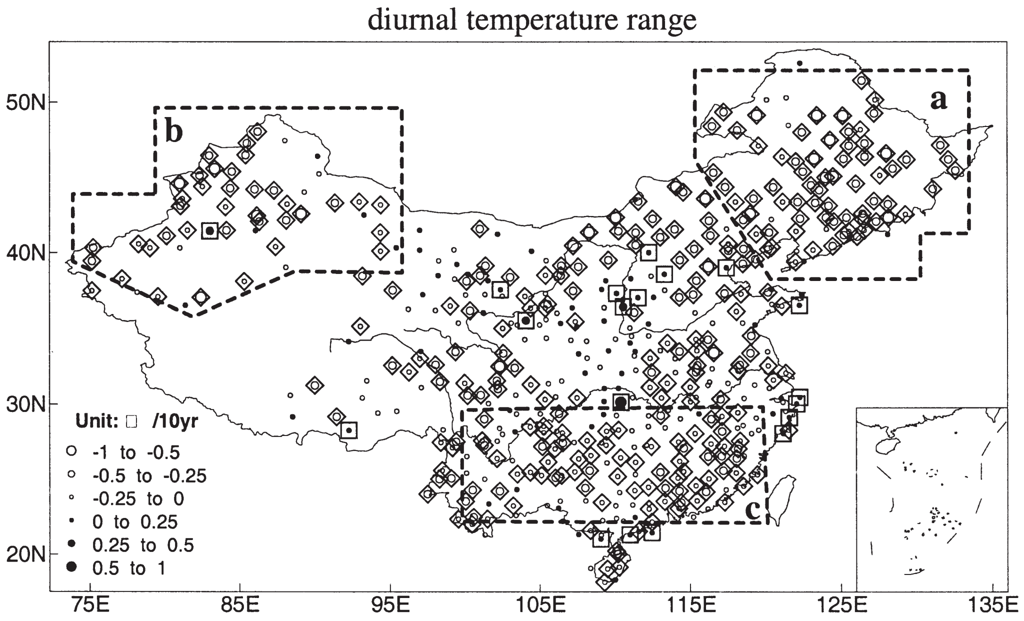


Fig. 2. Trend distribution (°C/10 yr) of diurnal temperature range (DTR) in China during 1961 to 2000. Solid dots denote increasing trend, squares indicate statistical significance at the 0.05 confidence level for the upward trend, circles denote decreasing trend and diamonds indicate statistical significance at the 0.05 confidence level for the negative trend. Dashed boxes indicate 3 regions in Northeast China (a), the Xinjiang region (b) and South China (c)

Table 2. Seasonal and annual trends in diurnal temperature range (DTR) for different regions indicated in Fig. 2 (units: °C/10 yr; all regions satisfy the 0.05 confidence level except DJF and SON in South China)

DTR	DJF	MAM	JJA	SON	ANN
Xinjiang	**−0.32**	**−0.31**	**−0.24**	**−0.16**	**−0.26**
Northeast China	**−0.37**	**−0.33**	**−0.25**	**−0.35**	**−0.33**
South China	−0.24	**−0.19**	**−0.18**	−0.06	**−0.17**

Zhou et al. (2004) showed a significant influence of urbanization on DTR decrease, as high as 0.20°C per decade, in Southeast China during the last 20 yr. This estimation in winter is a substantial proportion of the DTR decrease found in the present study for South China (Table 2).

As Fig. 4 shows, trends of cool days display a significant decrease in northern China, most obviously in the middle latitudes near 40° N along the Yellow River

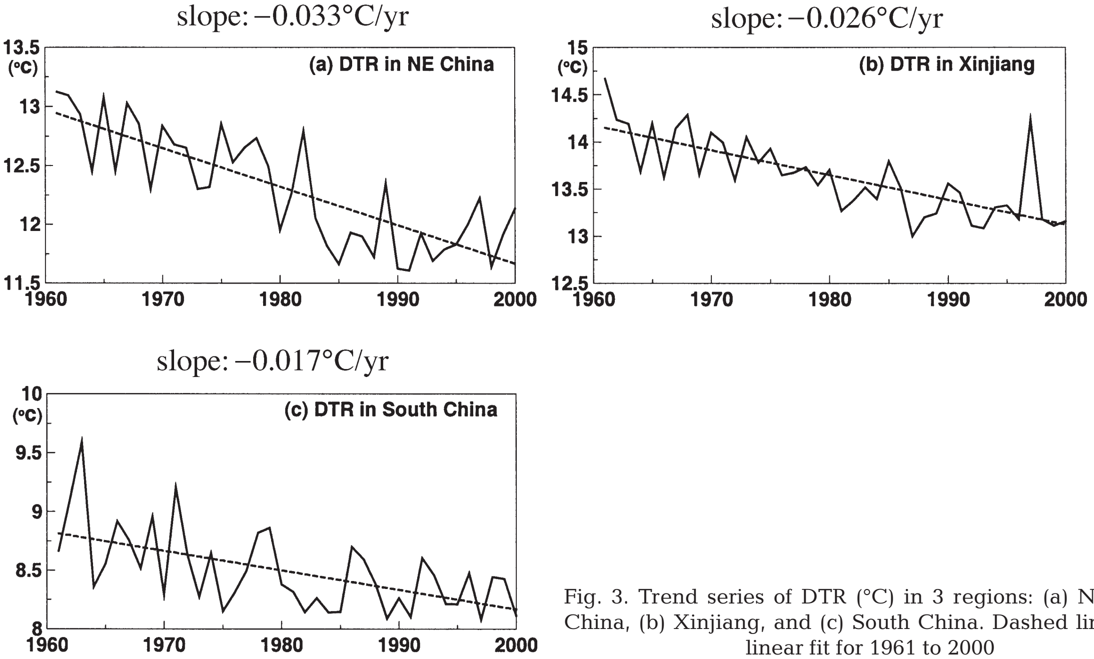


Fig. 3. Trend series of DTR (°C) in 3 regions: (a) Northeast China, (b) Xinjiang, and (c) South China. Dashed line is the linear fit for 1961 to 2000

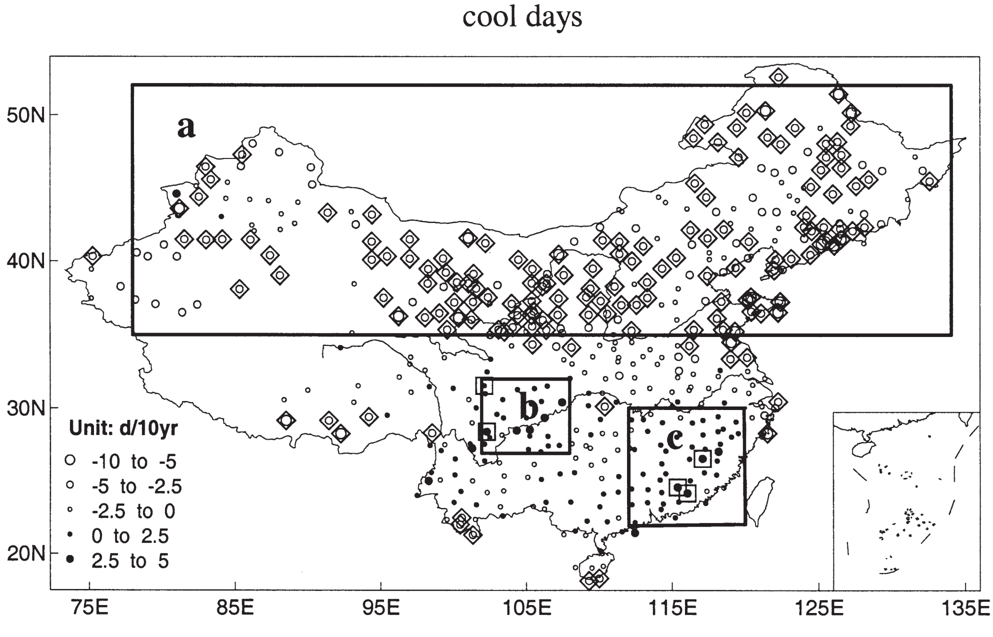


Fig. 4. Trend distribution of Tx10p (cool days). Symbols as in Fig. 2. The 3 boxes indicate northern China (a), the upper Yangtze River (b) and Southeast China (c)

valley, the Xinjiang region and Northeast China. Scattered stations with an upward trend can be found in South China, especially concentrated in the upper Yangtze River valley and Southeast China. Decreasing trends of cool days in northern China may be connected with the decreasing cyclone activity (Qian et al. 2002a) over high latitudes during the last 50 yr. Increasing trends of cool days in parts of South China are located in the regions of more rainfall (Qian et al. 2004) in the last 2 decades.

The regional time series of cool days averaged over the 3 regions (Fig. 4) indicate a decreasing trend in northern China and interannual variability in the upper Yangtze River (Sichuan Basin) and Southeast China (Fig. 5). In northern China, a decreasing trend with a slope of −0.324 d/yr appears after a short increase (peaking in 1969), and a decadal oscillation can be noted.

For the seasonal variation, Table 3 shows that cool days decrease commonly in winter (DJF) and northern China but increase in the other seasons over the Sichuan Basin and Southeast China. In Southeast China, the significant increase of cool days in summer is similar to the trend of rainfall increase (Qian et al. 2004).

Table 3. Seasonal and annual trends in Tx10p (d/10 yr) for cool days in different regions (**bold** values are within the 0.05 confidence level; units: d/10 yr)

Cool days	DJF	MAM	JJA	SON	ANN
Northern China	**−6.50**	−2.63	−1.27	−1.53	**−3.23**
Southeast China	−3.66	1.79	**4.04**	1.02	**0.94**
Sichuan Basin	−2.20	4.19	3.32	0.62	1.50

Trends of warm days are different from the trends of cool days and are displayed in Fig. 6. Most of the significant increasing trends are concentrated over the upper and middle Yellow River valley (UMYR, see box) as well as the northern part of the Xinjiang region and the northern part of Northeast China. Regional analysis shows that the increase is most obvious since the 1990s with the maximum in 1998. Some significant positive trends are concentrated in other regions, such as along the coast of South China and the Shandong Peninsula near the east coast, which is consistent with the results of neighboring countries such as Japan and Vietnam (Manton et al. 2001). Some studies from South Korea indicate a faster increase in maximum temperature and an increase of DTR during the latter part of the time series of 1954 to 1999, although we only find 3 stations in the Shandong Peninsula with DTR increase; more stations with an increasing trend of warm days are concentrated in the Shandong and Liaodong Peninsulas, which are close to the Korean Peninsula. However, for China as a whole, it is obvious that many areas show negative trends, especially in central eastern China.

The trends of both decreasing cool days (−3.54 d/10 yr) and increasing warm days (4.76 d/10 yr) over the UMYR are different (Fig. 6b,c). The difference between the most cool days (in 1967) and the least cool days (in 1998) is 42 d, and the difference of the least warm days (in 1964) and the most warm days (in 1998) is 59 d. Their seasonal variations can be noted in Table 4. Cool days significantly decreased in winter and warm days obviously increased in winter and autumn.

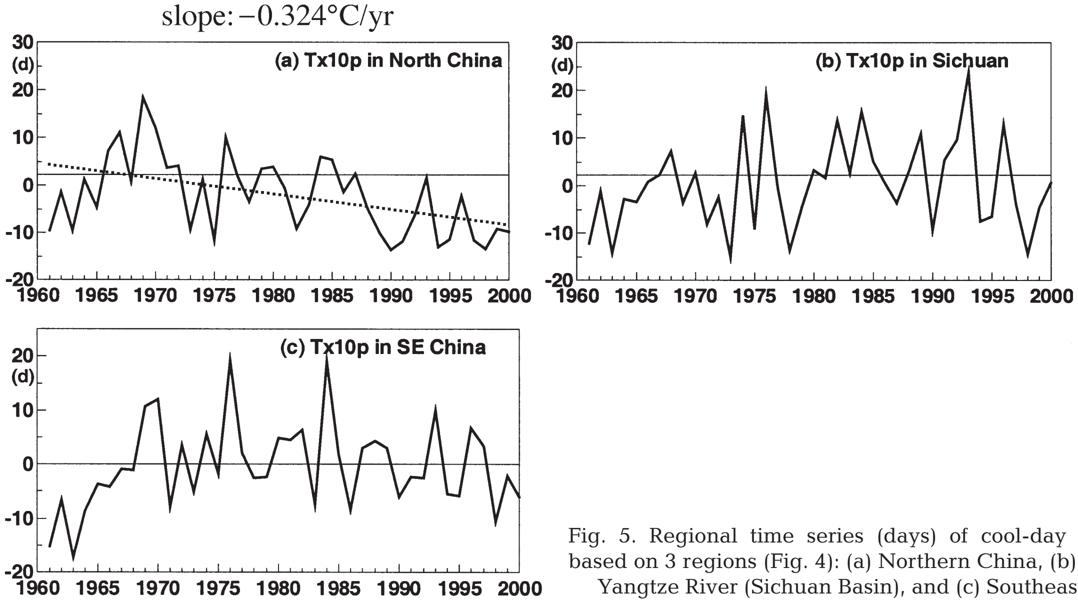


Fig. 5. Regional time series (days) of cool-day anomalies based on 3 regions (Fig. 4): (a) Northern China, (b) the upper Yangtze River (Sichuan Basin), and (c) Southeast China

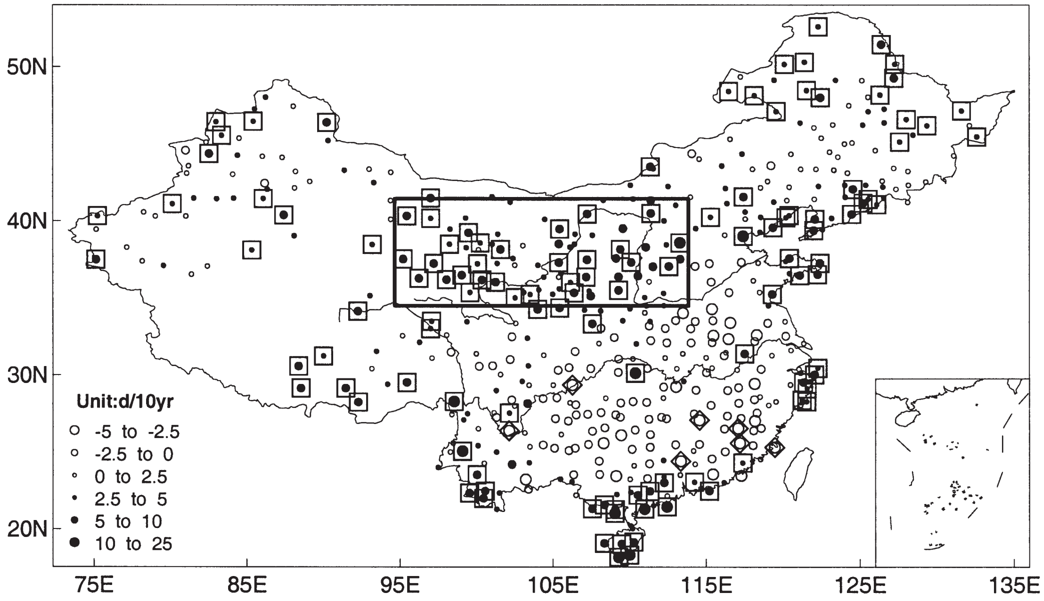
Trends of both cool nights and warm nights are shown in Fig. 7a,b. Zhai et al. (1999) found that mean minimum temperature increased more significantly than maximum temperature in China as a whole during 1951 to 1995. Mitchell (1961) and DeGaetano & Allen (2002) found that minimum temperature was more easily affected by urbanization than maximum temperature was. Urban heat islands may easily form during the night due to a possible factor that the boundary-layer wind speed influenced by buildings is larger in the daytime. Since urbanization in China is so prominent due to its rapid development, especially during recent decades, some effects of urbanization could not be eliminated completely, even though we omitted the 56 biggest cities from the dataset. For the reasons mentioned above, it was not surprising to see that both cool nights and warm nights have a more uniform trend distribution than the day temperature, except for a few stations.

Table 4. Seasonal and annual trends in Tx10p (d/10 yr) for cool days and Tx90p for warm days over the upper and middle Yellow River valley (**bold** values are within the 0.05 confidence level)

Trend	DJF	MAM	JJA	SON	ANN
Cool days	**−8.12**	−2.20	−0.41	−3.68	**−3.54**
Warm days	**5.38**	0.55	3.82	**9.28**	4.76

In northern China there is a decreasing trend in cool nights and an increasing trend in warm nights. The time series in both northern and South China show a similar variation (Fig. 8). Since the mid-1980s the amplitude of interannual variations became larger, and 1998 marks the year with the most warm nights and the least cool nights. Seasonal analysis shows that cool nights significantly decreased and warm nights

(a) warm days



(b) cool days (slope: −0.354 d/yr)

(c) warm days (slope: 0.476 d/yr)

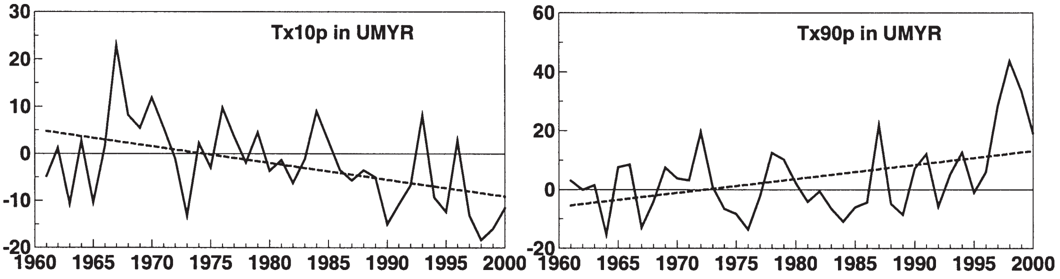
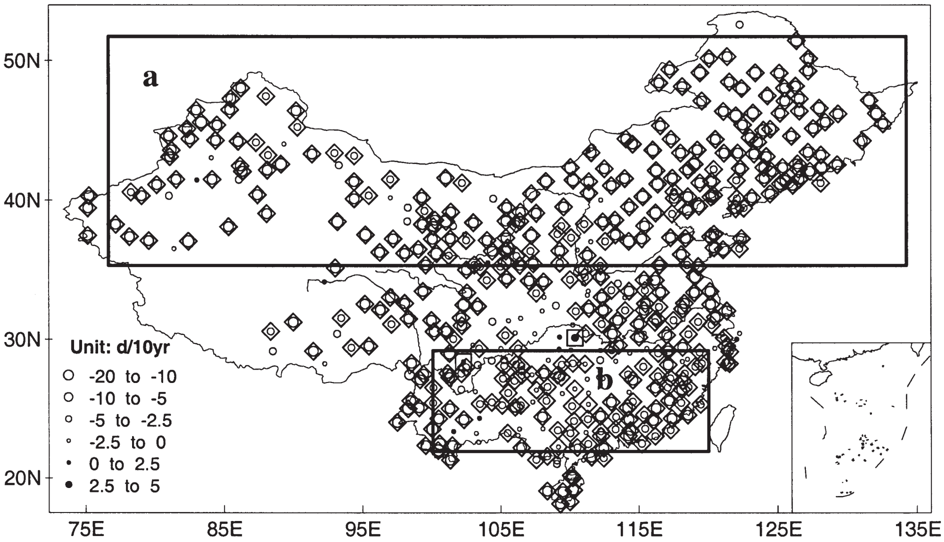


Fig. 6. (a) Trend distribution of warm days (Tx90p); symbols as in Fig. 2; (b) time series (days) of the cool-day anomaly; and (c) time series (days) of the warm-day anomaly in the same box over the upper and middle Yellow River (UMYR)

(a) cool nights



(b) warm nights

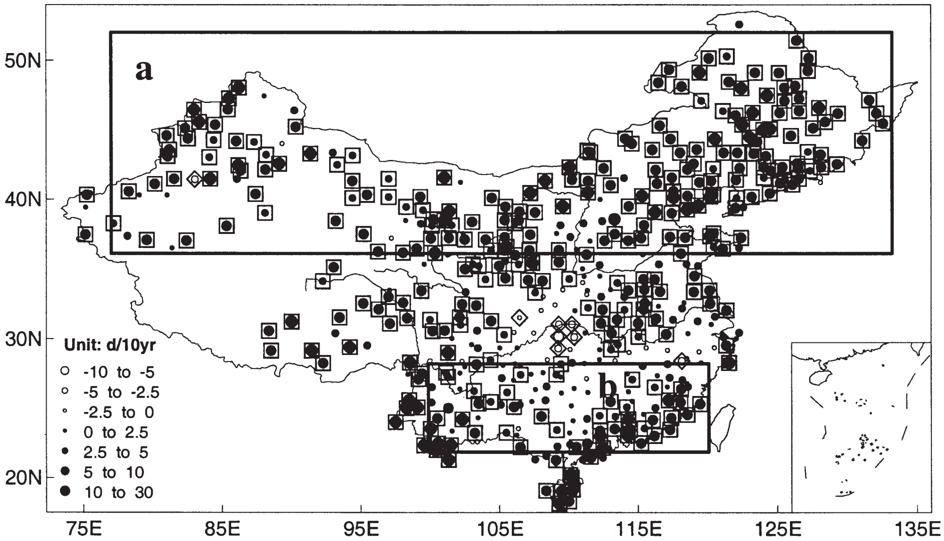
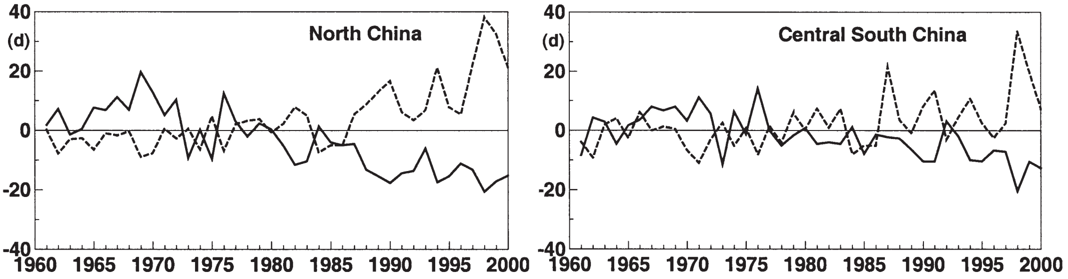


Fig. 7. Trends of (a) Tn10p (cool nights) and (b) Tn90p (warm nights). Symbols as in Fig. 2. The 2 boxes indicate northern China (upper box) and South China (lower box)


(a) Northern China

(b) Central South China

Fig. 8. Time series for the cool-night anomaly (solid line) and the warm-night anomaly (dashed line) in (a) northern China (upper box in Fig. 7) and (b) central South China (lower box in Fig. 7)

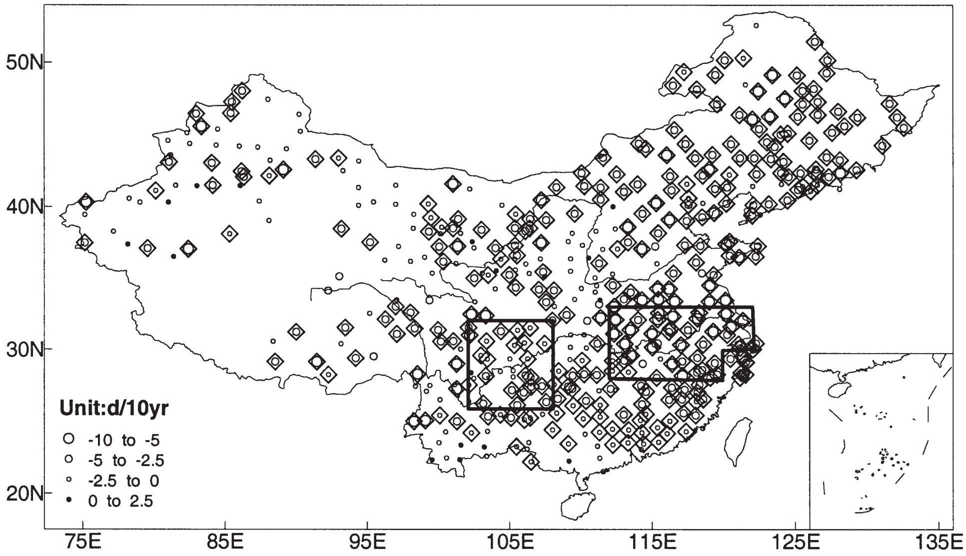
dramatically increased for all seasons, particularly in winter over northern China (Table 5). In South China, the decrease of cool nights was measured in winter and the increase of warm nights (7.02 d/10 yr) was detected in summer.

Table 5. Seasonal and annual trends (d/10 yr), as for Table 4 except for Tn10p (cool night) and Tn90p (warm night) in South and northern China

Trend	DJF	MAM	JJA	SON	ANN
North China					
Cool night	**−10.91**	**−6.86**	**−6.62**	**−4.34**	**−7.07**
Warm night	**9.37**	**5.01**	**7.45**	**5.70**	**6.83**
South China					
Cool night	**−8.59**	−2.24	−2.41	−2.50	**−3.92**
Warm night	2.83	1.94	**7.02**	2.36	**3.64**

The number of frost days decreased significantly over most of mainland China (Fig. 9), and few stations showed an increase in frost days. This result is basically consistent with that of Zhai & Pan (2003). Here, 2 time series (boxes in Fig. 9a) of frost days are shown in Fig. 9b. Regional frost days over the upper Yangtze River and the lower Yangtze River have the least frost days in the 1990s. A 7 to 8 yr oscillation of the frost days over the upper river and a significant decreasing trend can be observed from these 2 curves. The difference in number of annual frost days in the lower Yangtze River had a maximum of 35 d between 1967 and 1994. Decadal and interannual variability of frost days exists in the 2 series. Frost days in spring (MAM) over the upper valley and in autumn (SON) over the lower valley also have a significant decreasing trend for the mean area, but winter (DJF) does not.

(a) frost days



(b) time series

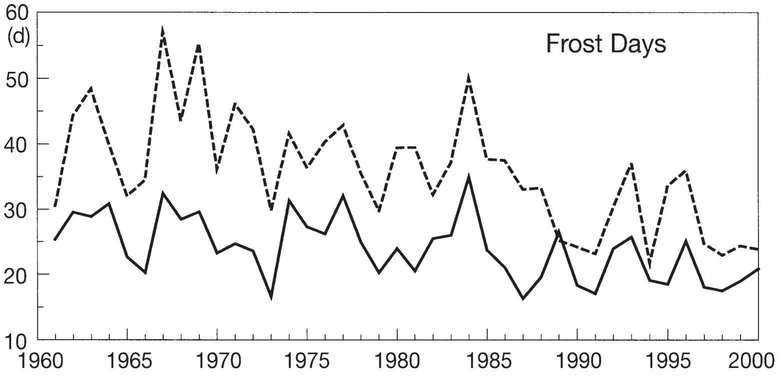
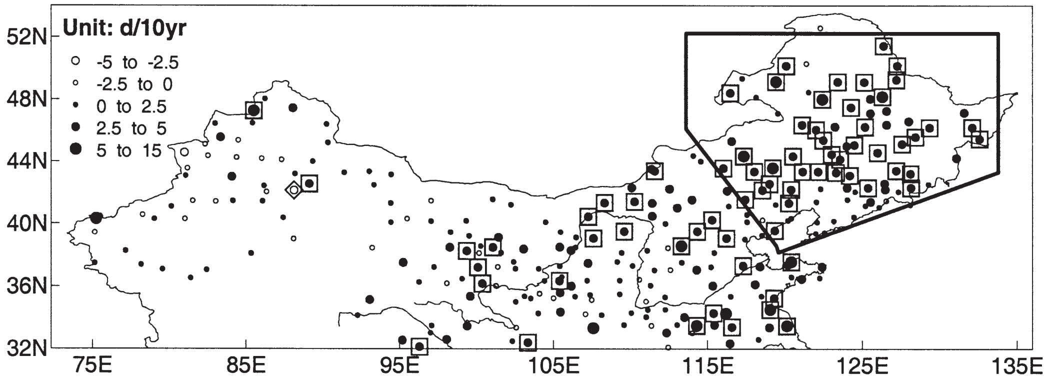


Fig. 9. (a) Trend distribution of frost days and (b) time series (days) over the upper (solid line) and the lower (dashed line) Yangtze River valley areas (2 boxes in a). Symbols as in Fig. 2

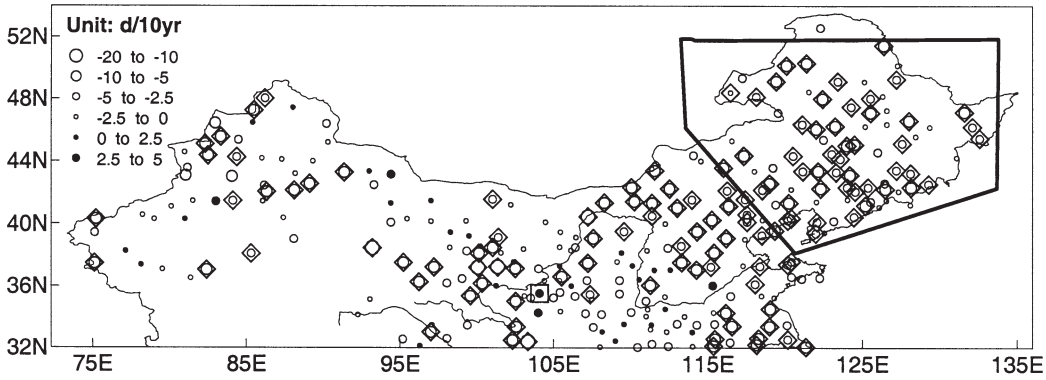
As shown in Fig. 10a, the growing seasonal length increased in both North China and Northeast China by about 0.5 d/yr. Frost seasonal length (Fig. 10b) decreased in most parts of northern China due to the increasing minimum temperature. Ice days (Fig. 10c) decreased in North China and the southern part of Northeast China, but a slight increase can be found in the northern Xinjiang region.

Some major time series from different regions boxed in Fig. 10 are plotted in Fig. 11. In Northeast China, there are opposite trends during 1961 to 2000 between GSL (growing seasonal length) and FSL (frost seasonal length). The FSL decreased from 220 to 230 d/yr in the 1960s to a minimum of <200 d/yr in 1998, while the GSL increased from about 190 d/yr in the late 1980s to more than 210 d/yr during the 1990s (Fig. 11a).

(a) growing seasonal length



(b) frost seasonal length



(c) ice days

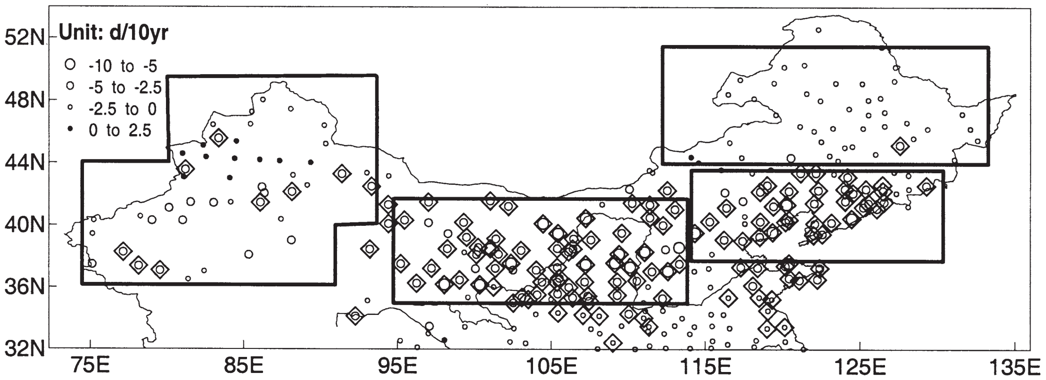
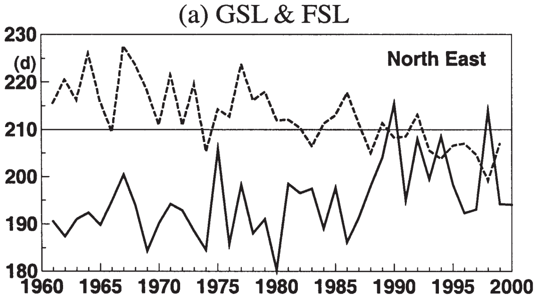
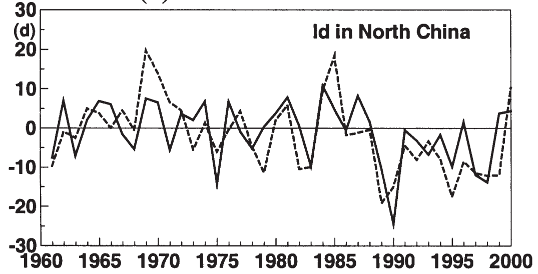


Fig. 10. Trend distributions of (a) growing seasonal length, (b) frost seasonal length, and (c) ice days in northern China during 1961 to 2000. Symbols as in Fig. 2. Detailed information about the indices can be found in Table 1

(a) GSL & FSL



(b) Id in northeast China



(c) Id in northwest China

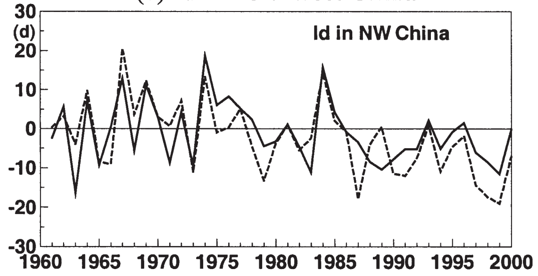


Fig. 11. Time series for different boxes and different indices. (a) GSL (growing seasonal length; solid line) and FSL (frost seasonal length; dashed line) in Northeast China based on Fig. 10a & b, (b) anomalies of ice days for the boxes in the northern part (solid line) and southern part (dashed line) of Northeast China, and (c) anomalies of ice days for the boxes in the Xinjiang region (solid line) and centered over the upper-middle Yellow River valley (dashed line)

A significant trend of ice days in the southern part of Northeast China (Fig. 10c) is contributed to by more ice days from the late 1970s to the mid-1980s and less ice days since 1988 with a mean trend of –3.2 d/10 yr (Fig. 11b). A decadal transition starting from the late 1980s can be found from the series of ice days in the northern part of Northeast China (Fig. 11b). A decreasing trend of ice days in both the Xinjiang region and the upper Yellow River valley was observed after the mid-1970s (Fig. 11c). Several oscillations with a period of about 10 yr can be noted from the series of ice days over the Xinjiang region. An ice-day difference of about 20 d in the years 1967, 1974 and 1984 was recorded.

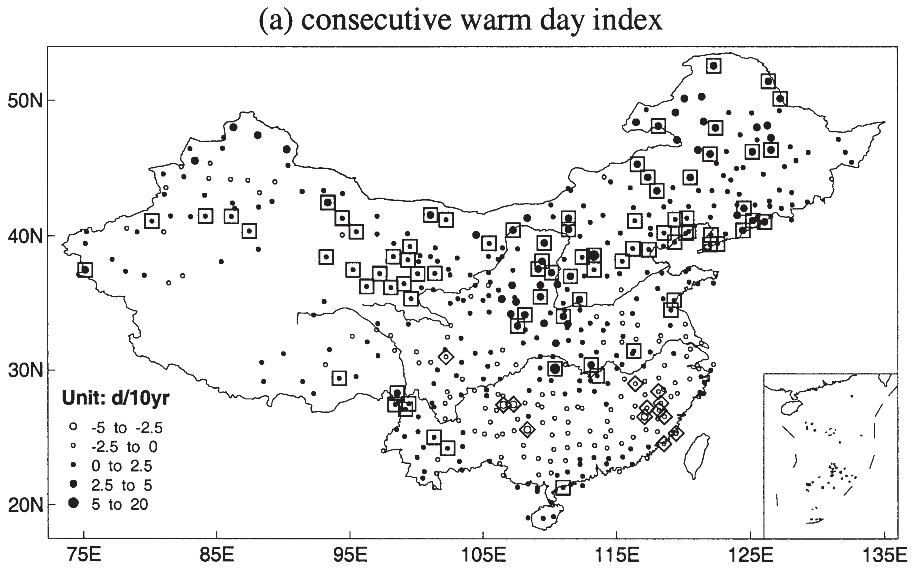
As shown in Fig 12a, consecutive warm days increased in northern China but a decrease of consecutive warm days can be noted at several spots in southern China. Consecutive cold days decreased largely in the Xinjiang region, North China along the Yellow River valley and the southern part of Northeast China, as well as along the southeast coast of the country. These areas are the major regions of cold air outbreak.

5. DISCUSSION

For the annual mean, the cool nights decreased in almost the whole of China. In examining the seasonal contribution, cool nights largely decreased in winter and at 232 stations (nearly half of the total) stations there was a negative trend of about –2.5 to –5 d/10 yr; moreover several stations decreased with absolute values greater than 5 d/10yr (Fig. 13a). Most of the stations with a faster decrease were in northern China and eastern China. In spring (Fig. 13b), a decrease in cool nights is mainly located in North China and Northeast China. Another major contribution of the decrease in cool nights comes from summer, except in the region of the mid-low Yangtze River valley (Fig. 13c). In autumn (Fig. 13d), cool nights decreased mainly in North China, Northeast China and the eastern Tibetan Plateau. Increases of regional cool nights are concentrated along the mid-low Yangtze River for summer and autumn.

In the annual mean, warm days increased mainly in the mid-upper Yellow River and on the coast of South China including Hainan Island. The increase in warm days is attributed to higher temperatures in winter over northern China and in summer over western China and along the coast of South China, but a decreasing trend is noted in the basins of the Yangtze and Huaihe Rivers (Fig. 14). In the winter season, regional warm days increased in Northeast China and the UMYR, but warm days decreased in southern China. In spring, warm days increased significantly only near the coast of South China while warm days decreased in the lower Yellow River. The warm day decreases in the mid-low Yangtze River are linked to increased summer rainfall (Qian et al. 2004). In autumn, the increasing trend of warm days in the entire Yellow River valley coincides with the decreased rainfall in this season (Qin 2004).

Trends in temperature indices have strong regional characteristics and seasonal variations in China. Temperature variations are related to precipitation variations. Usually, less rainfall, such as in autumn in the mid-upper Yellow River, will result in increased warm days and less cool nights while more summer rainfall


(a) consecutive warm day index

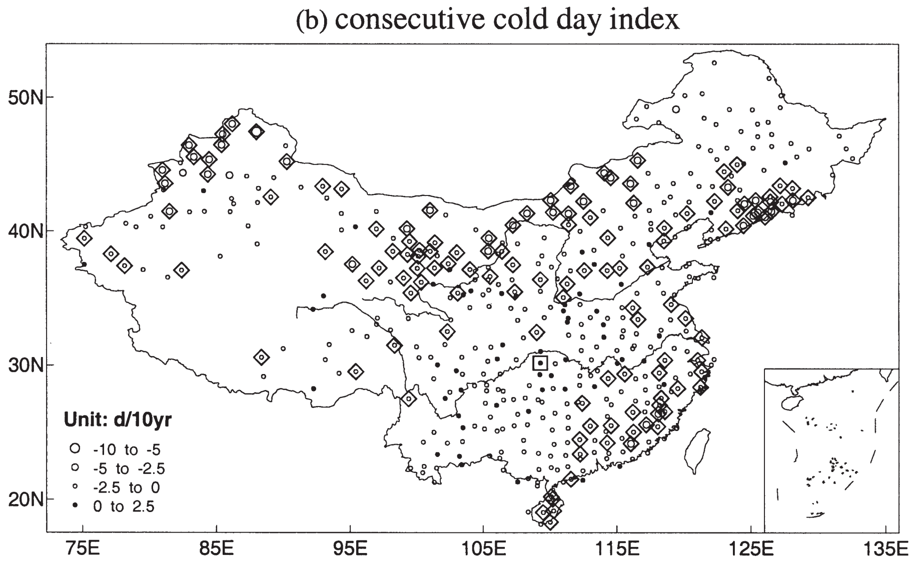

(b) consecutive cold day index

Fig. 12. Trends in (a) consecutive warm day index (d/10 yr) with consecutive cases of $T_{max} > 5°C$ with respect to the climate mean state and (b) consecutive cold day index (d/10 yr) with consecutive cases of $T_{min} < 5°C$ with respect to the climate mean state in China during 1961 to 2000. Details of indices can be found in Table 1

along the mid-low Yangtze River will decrease warm days and increase cool nights. Seasonal and annual precipitation trends in China for the last 4 decades can be referenced from Qin (2004) or Qin & Qian (2004). Changes in cloud cover and soil evaporation could also influence the temperature variations or the DTR (Zhou et al. 2004).

Other significant influences on the trends of DTR and temperature indices have been investigated in recent years and may be caused by urbanization (Kalnay & Cai 2003, Zhou et al. 2004), industrial aerosols (Xu 2001, Wild et al. 2004), and non-climate factors such as population, economic activity, and local energy usage (Laat et al. 2004, McKittrick & Michaels 2004). These influences become particularly significant in China because of its rapid urbanization and economic activity in the past 2 decades.

By using the daily temperature series at 498 stations, we found that the reduction in the number of extremely cold days in China and the increase in the number of extremely hot days in northern China are consistent with the report of Frich et al. (2002) but there were several stations with a decreasing trend in the number of extremely hot days in South China.

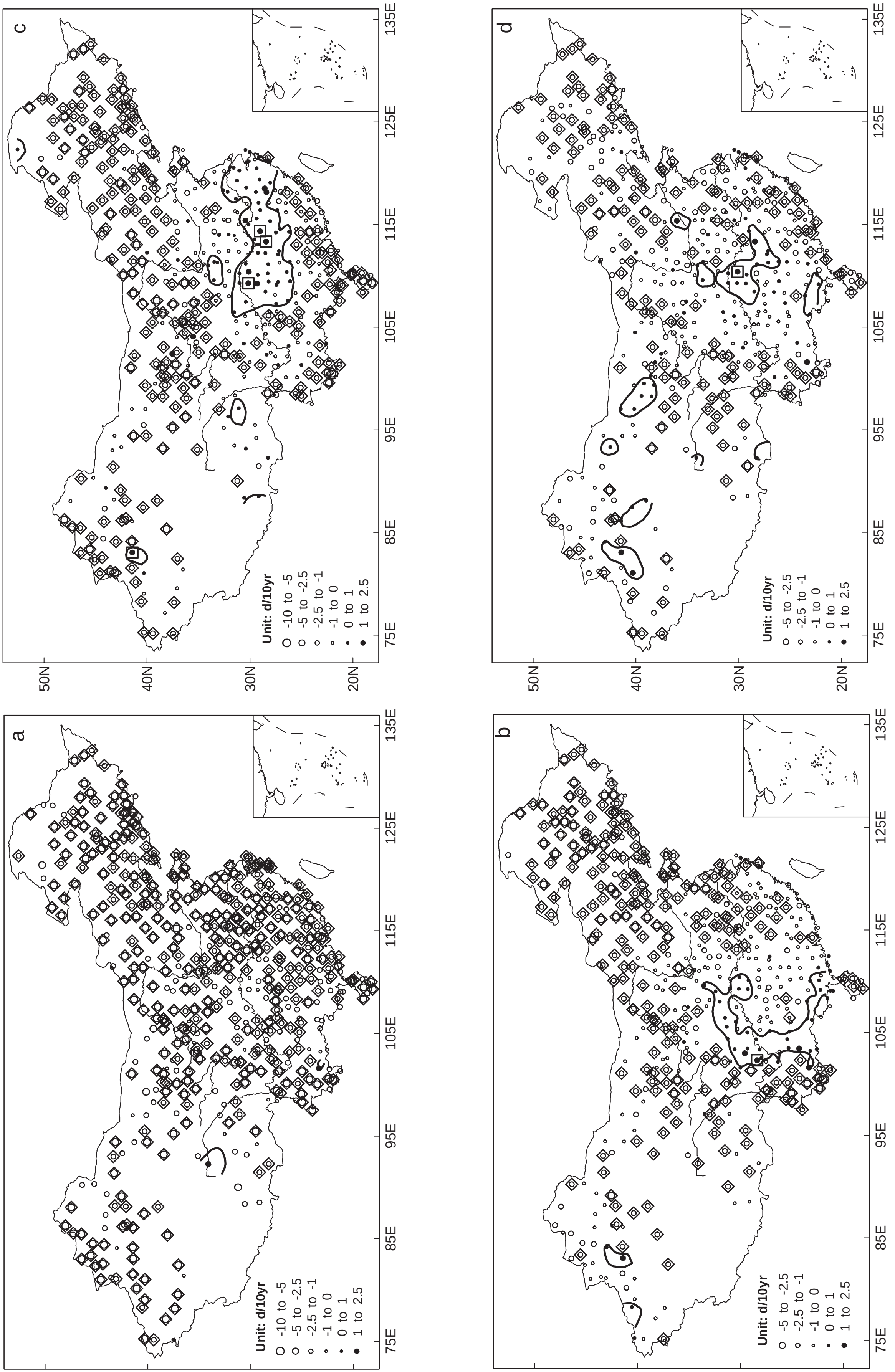


Fig. 13. Trends (d/10yr) of Tn10p (cool nights). As Fig. 7a, except that seasonal contributions are shown. (a) Winter, (b) spring, (c) summer, and (d) autumn. The zero line is highlighted. Symbols as in Fig. 2

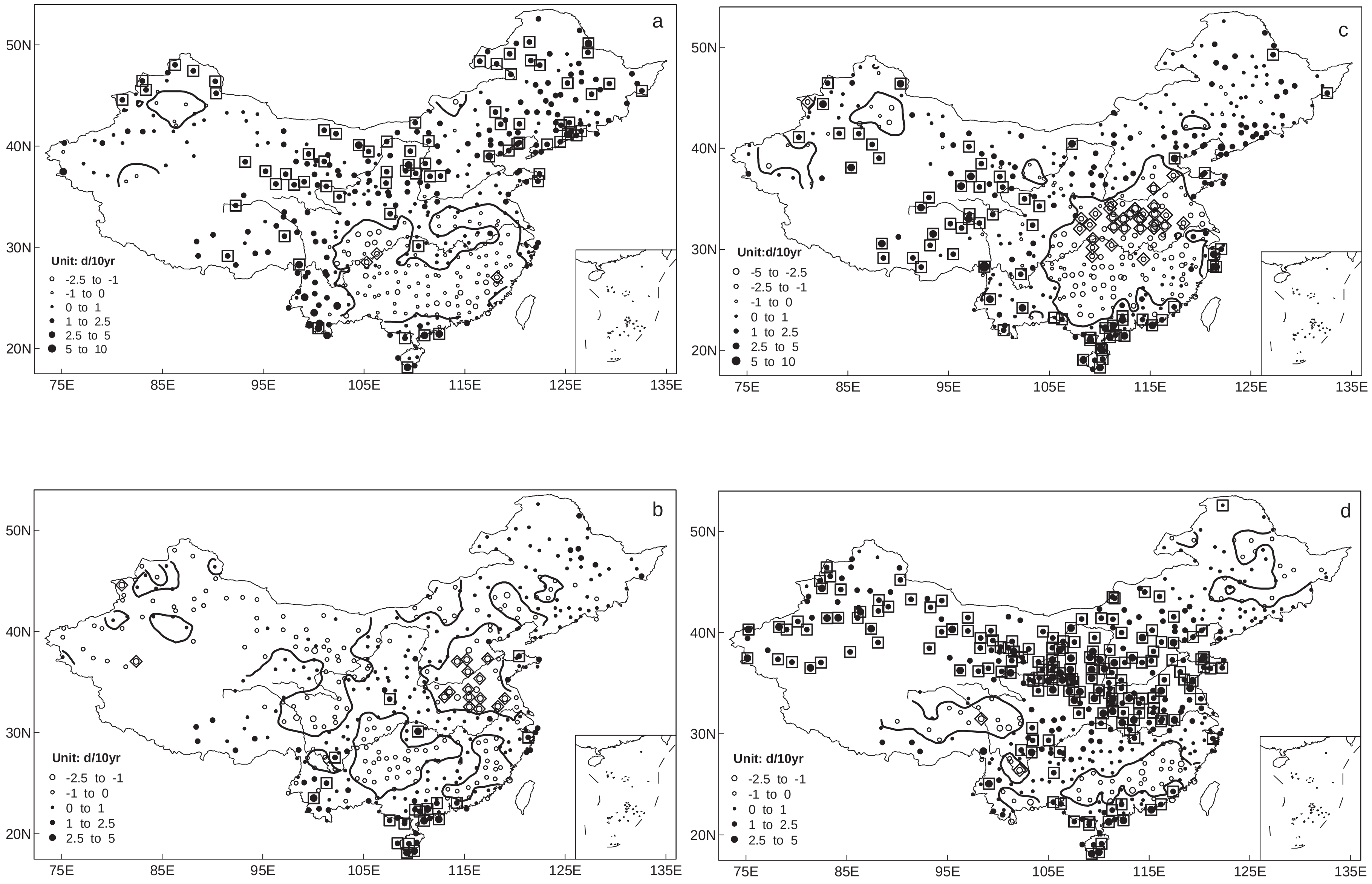


Fig. 14. Trends (d/10yr) of Tx90p (warm days). As Fig. 7b except that seasonal contributions are shown. (a) Winter, (b) spring, (c) summer, and (d) autumn. The zero line is highlighted. Symbols as in Fig. 2

6. CONCLUSION

Trends in indices derived from Chinese daily maximum and minimum temperatures from 1961 to 2000 were studied. The major conclusions are summarized as follows.

(1) Regional features of climate change are detected from the daily air temperature record of mainland China. Decreasing trends of diurnal temperature range are found in mainland China as a whole during 1961 to 2000, and stronger decreases are located in Northeast China, central South China and the Xinjiang region. This trend is consistent with that detected from Asia and lands in the Northern Hemisphere (Frich et al. 2002). Trends of cool days display a significant decrease in the middle latitudes near 40° N along the Yellow River valley. Increasing trends of warm days are also located in the UMYR and other regions such as along the coast of South China, while decreasing trends are scattered in the central regions of East China. Since minimum temperature may be greatly influenced by the prevalent urbanization in China, minimum temperature (*Tn*) indices show a consistent trend distribution over the country except for some stations scattered in the middle Yangtze River valley and the southern part of the Yangtze River. The increase in warm nights and decrease in cool nights are also consistent with other results.

(2) The number of frost days decreased significantly in most of mainland China. GSL increased in North China and Northeast China by about 0.5 d/yr. FSL decreased in most parts of northern China due to the increasing minimum temperature. Ice days decreased in North China and the southern part of Northeast China, but a slight increase can be found in the northern Xinjiang region.

(3) Consecutive warm days increased in northern China but a decrease can be noted in southern China in a few spots. Consecutive cold durations have decreased largely in the Xinjiang region, in North China along the Yellow River valley and in the southern part of Northeast China, and along the southeast coast of the country. These areas are the major regions of cold air outbreak.

(4) Cool nights have largely decreased in winter as a whole and the trend is about –2.5 to –5 d/10 yr. Another contribution of cool nights comes from summer except for the region of the mid-low Yangtze River valley. The contribution of warm days is attributed to the higher temperature in winter over northern China and in summer over western China and along the coast of South China, but a decreasing trend is noted in the basin of the Yangtze and Huaihe Rivers. Temperature indices have strong regional characteristics and seasonal variations in China. Temperature variations are related to precipitation variations. Usually, less rainfall such as in autumn in the mid-upper Yellow River causes more warm days and less cool nights, while more summer rainfall along the mid-low Yangtze River decreases the warm days and increases the cool nights.

Temperature indices analyzed in this paper show some regional features. Some non-climate factors also influenced these indices, but the time series of only 40 yr may be a little too short for a quantitative trend analysis. Changes in temperature indices and their trends have a good correlation with the change of the mean state of climate. Some detailed analyses of the seasonal variations and their causes may be more instructive.

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