Changing Trends of Daily Temperature Extremes with Different Intensities in China

WANG Zunya[1*] (王遵娅), DING Yihui[1] (丁一汇), ZHANG Qiang[2] (张　强), and SONG Yafang[1] (宋亚芳)

1 *National Climate Center, China Meteorological Administration, Beijing* 100081

2 *China Meteorological Administration, Beijing* 100081

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ABSTRACT

By comparing two sets of quality-controlled daily temperature observation data with and without the inhomogeneity test and adjustment from 654 stations in China during 1956–2004 and 1956–2010, impacts of inhomogeneity on changing trends of four percentile temperature extreme indices, including occurrences of cold days, cold nights, warm days, and warm nights with varying intensities, were discussed. It is found that the inhomogeneity affected the long-term trends averaged over extensive regions limitedly. In order to minimize the inhomogeneity impact, the 83 stations identified with obvious inhomogeneity impacts were removed, and an updated analysis of changing trends of the four temperature extreme indices with varying intensities during 1956–2010 was conducted. The results show that annual occurrences of both cold nights and cold days decreased greatly while those of warm nights and warm days increased significantly during the recent 20 years. The more extreme the event is, the greater the magnitude of changing trends for the temperature extreme index is. An obvious increasing trend was observed in annual occurrences of cold days and cold nights in the recent four years. The magnitude of changing trends of warm extreme indices was greater than that of cold extreme indices, and it was greater in northern China than in southern China. Trends for summer occurrence of cold days were not significant. Decreasing trends of occurrences of both cold nights and cold days were the greatest in December, January, and February (DJF) but the least in June, July, and August (JJA), while increasing trends of warm nights were the greatest in JJA. Cold nights significantly decreased from 1956 to 1990, and then the decreasing trend considerably weakened. The decreasing trend also showed an obvious slowdown in recent years for occurrence of cold days. However, increasing trends of warm nights and warm days both have been accelerated continuously since the recent decades. Further analysis presents that the evolution of the trends for occurrences of the four temperature extreme indices was dominated by the changes in northern China.

Key words: temperature extremes, cold nights, cold days, warm nights, warm days, changing trend

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1. Introduction

It is pointed out that global surface temperature has increased 0.74℃ in recent 100 years in Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (Solomon et al., 2007). Under the background of global warming, the surface temperature has increased significantly in China, with the amplitude of 0.5–0.8℃ in recent 100 years and the increasing speed of 0.22℃ (10 yr)$^{-1}$ in recent 50 years (Compiling Committee of China's National Assessment on Climate Change, 2007). Because both the shifts in climatic mean values and changes in anomalies can affect the probability of frequency of extremes (Ding et al., 2003), changing trends of extreme events, especially temperature extremes, have been paid great attention and regarded as an important part of global change. Many studies (Karl et al., 1993; Cooter and Leduk, 1993; Easterling et al., 2000) have shown that global frequencies of both extreme low temperature events and frost days decreased in the past decades. Similar changes were observed in the U.S. and Canada (Karl et al., 1984; Cooter and Leduk, 1993; Bonsal et al., 2001; Alexander et al., 2006). Manton et al. (2001)

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*Corresponding author: wangzy@cma.gov.cn.

found that hot days and warm nights increased obviously while cold days and cold nights decreased. As shown in IPCC AR4, changes of temperature extremes have been observed worldwide in the recent 50 years: the frequencies of cold days, cold nights, and frost days decreased while the frequencies of hot days, warm nights, and heat waves increased (Solomon et al., 2007).

Characters and changes of temperature extremes and correlated extreme events in China were studied. The trends of extreme temperatures in China were analyzed (Ren and Zhai, 1998; Ma et al., 2003; Zhai and Pan, 2003a, b). It is found that both the lowest and the highest temperatures increased in recent decades, with the increasing trend of the lowest temperature being much greater than that of the highest one. On the other hand, varieties of indices of temperature extremes were defined and relevant changes were discussed (Huang and Qian, 2008, 2009; Zhou and Ren, 2010). Despite of differences in definition, similar results were obtained as that the frequencies of low temperature extremes decreased significantly in China, especially over Northeast China, North China, and the Tibetan Plateau. Additionally, some extreme low temperature events have changed. For example, numbers of days with daily minimum temperature below 0℃ in northern China decreased obviously, suggesting that non-frost period has gradually lengthened there (Ding et al., 2003); and frequencies of cold waves significantly decreased over the past five decades in China (Wang and Ding, 2006).

Previous studies revealed that both extreme temperature events and temperature extremes showed significant changing trends not only in China but in other regions of the world under global warming during past decades. However, there are still questions to be answered: (1) What differences are there in changing trends of temperature extreme indices with varying intensities? (2) What are the characters of the evolution trends of temperature extreme indices in recent decades in China? (3) How does the inhomogeneity impact changing trends of temperature extreme indices? The above problems will be discussed in this paper. Moreover, another important purpose of this paper is to compare and validate previous results of changes of temperature extremes in China, using the updated high quality datasets.

In Section 2, the datasets, methods, and temperature extreme indices are introduced. Section 3 discusses the impact of inhomogeneity of datasets on changing trends. Long-term trends of temperature extreme indices with different intensities in China are analyzed in Section 4. Evolution characters of temperature extremes are shown in Section 5. Finally, the main results are concluded in Section 6.

2. Data, indices, and methods

2.1 Data quality and homogeneity

Two datasets compiled and provided by the National Meteorological Information Center (NMIC), China Meteorological Administration (CMA) are adopted in this study. One is daily mean, maximum, and minimum surface temperature records from 731 surface weather stations in China from 1 January 1951 to 31 December 2004, with the inhomogeneity detection and adjustment being carried out (Liu and Li, 2003; Li et al., 2004); the other is the dataset of the same variables from the same 731 stations from 1 January 1951 to 31 December 2010, but without the inhomogeneity detection and adjustment being processed. As there were few observation stations in western China before 1956, both datasets are analyzed from then on.

The data quality control was conducted by the NMIC, which includes extreme value control, consistency check, and spatial consistency test (Liu and Li, 2003). During these processes, data at 48 stations were eliminated for insufficient records, and data at additional 29 stations were not used in this study because their time series are shorter than 30 yr. Finally, data from the same 654 stations were chosen from the two datasets.

Additionally, spatial and internal consistency checks were performed to minimize the impact of taking the error records as climatic extremes, using the method introduced by Pan and Zhai (2002).

2.2 Definition of temperature extreme indices

The World Meteorological Organization (WMO)

Commission for Climatology/CLIVAR Expert Team on Climate Change Detection Monitoring and Indices (ETCCDMI) developed a set of extreme indices. Among them, the 10th percentile was used to define occurrences of cold nights, cold days, warm nights, and warm days. In this paper, the 10th (90th), 5th (95th), and 1st (99th) percentile were individually chosen to get the thresholds of the above 4 indices.

The threshold was calculated for each calendar day and for each station. Then, 366 thresholds were obtained for any station. Specifically, for a given day k, the minimum (maximum) temperature of each day from $k-3$ to $k+3$ in each year during 1971–2000 were arranged in ascending (descending) order. For this series, the following equation was used to calculate the serial number m corresponding to the probability P:

$$P = \frac{m - 0.31}{n + 0.38},$$

where n denotes the sample size and m the serial number.

That is, when $P = 0.05$, $m = \langle 0.05 \times (n+0.38) + 0.31 \rangle$, where $\langle\ \rangle$ denotes rounding down to the nearest integer. Then, the threshold of the 5th percentile for day k was obtained by interpolation of the sample x_m and x_{m+1} in the ascending (descending) series. For example, the 5th percentile threshold of a series with 30 samples is the interpolation of x_1 and x_2. This method is easy to calculate, with results similar to those of the Gammar distribution (Bonsal et al., 2001).

2.3 Methods

The least square method was used to calculate the linear trend coefficient, and the correlation test was conducted to verity the significance (Wei, 1999). The time series for China were derived by grid-box area weighted averages (Jones and Hulme, 1996). The Mann-Kendall test (Mann, 1945; Goossens and Berger, 1986) was carried out to check the climatic abrupt changing point.

3. Impacts of inhomogeneity on changing trends

Figure 1 shows two time series of annual occurrence of cold nights with the 10th percentile threshold for China derived individually from the homogeneous and the inhomogeneous datasets. It can be seen that the difference was not obvious and mainly observed before the mid 1960s. Decreasing trends were also significant under the confidence level of 5%, with linear trend coefficients being –8.28 and –7.82 day (10 yr)$^{-1}$ for the homogeneous and the inhomogenous dataset, respectively. The magnitude of decreasing trend derived from the inhomogeneous dataset was only 5.9% greater than that from the homogenous dataset, suggesting that the impact of inhomogeneity on the long-term changing trend averaged over an extensive region is limited.

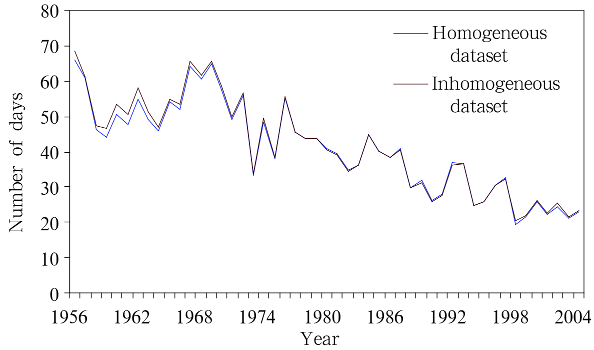

Fig. 1. Time series of annual occurrence of cold nights with the 10th percentile threshold for China derived individually from the homogenous and the inhomogeneous datasets during 1956–2004.

Differences of changing trends for annual occurrence of cold nights with the 10th percentile thresholds between the homogeneous and the inhomogeneous datasets for each station of China were calculated and standardized. Figure 2 shows that absolute standardized differences were below 2 for most stations but up to 2 at 83 stations. After those 83 stations were excluded, two time series of annual occurrence of cold nights with the 10th percentile threshold derived individually from the homogeneous and the inhomogeneous datasets were almost the same (Fig. 3), with the changing trends being nearly identical.

Same analyses were carried out to all four temperature extreme indices with varying intensities, and similar results were obtained. The impact of inhomogeneity on changing trends of the 4 extreme indices

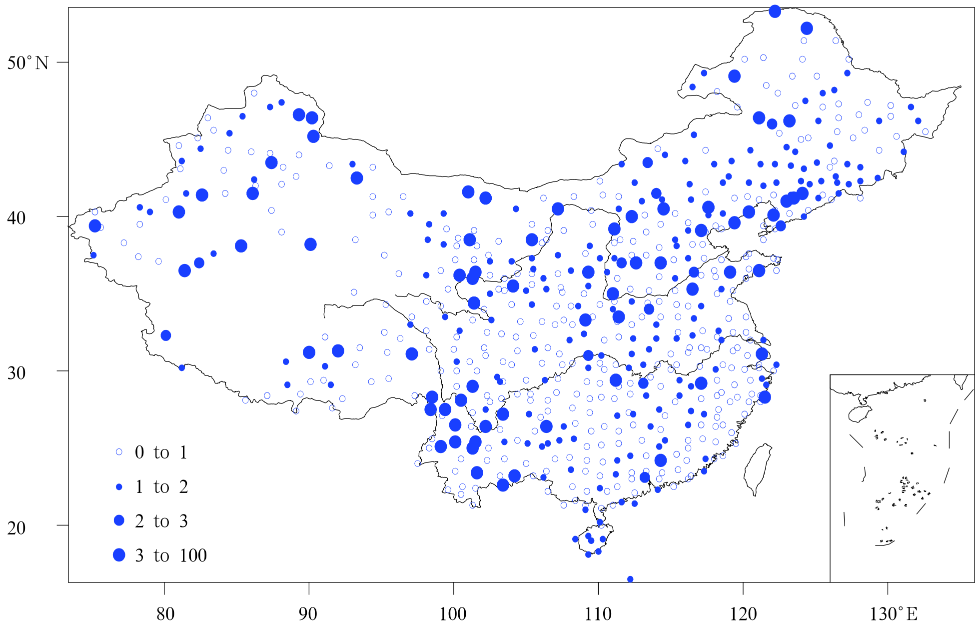

Fig. 2. Absolute standardized differences for changing trends of annual occurrence of cold nights with the 10th percentile threshold between the homogenous and inhomogeneous datasets during 1956–2004.

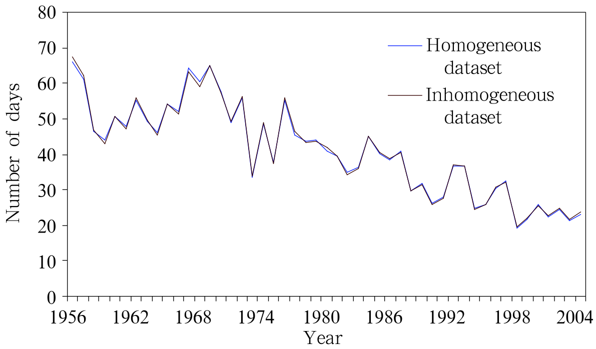

Fig. 3. As in Fig. 1, but for 83 stations with relatively obvious impact of inhomogeneity. These stations were removed from the inhomogeneous dataset.

was below 10%. In the following analysis, above 83 stations were removed from the inhomogeneous dataset to minimize the impact of inhomogeneity. That is, data from 571 stations were used to recalculate the changing trends of the 4 extreme indices.

4. Trends of temperature extreme indices with different intensities in China

4.1 Temporal features

Figure 4 shows time series of annual occurrence of temperature extreme indices with varying intensities between 1956 and 2010. It can be seen that annual occurrences of both cold nights and cold days decreased, while those of warm nights and warm days increased significantly. Oscillations were obvious before the 1970s and annual occurrence of cold nights decreased from then on. The Mann-Kendall test showed an abrupt decreasing point in the early 1980s. After then, annual numbers of cold nights were almost below normal. The annual number of cold days after the late 1980s was less than the climatic mean value and the decreasing magnitude was much smaller than that of cold nights. Increasing trends of annual occurrences of warm nights and warm days were similar and significant, especially in the recent two decades, but the magnitude of the former was greater than that of the latter. All these results were coherent with those revealed by previous studies (Zhou and Ren, 2010; Zhai and Pan, 2003a, b). Even linear trend coefficients of annual numbers of the 4 extreme indices with the 10th percentile threshold were much close to those calculated by Zhou and Ren (2010).

Except the above findings, a few new results were obtained. First, with the strengthening of the intensity, the magnitude of changing trends for annual occurrences of a temperature extreme index increased

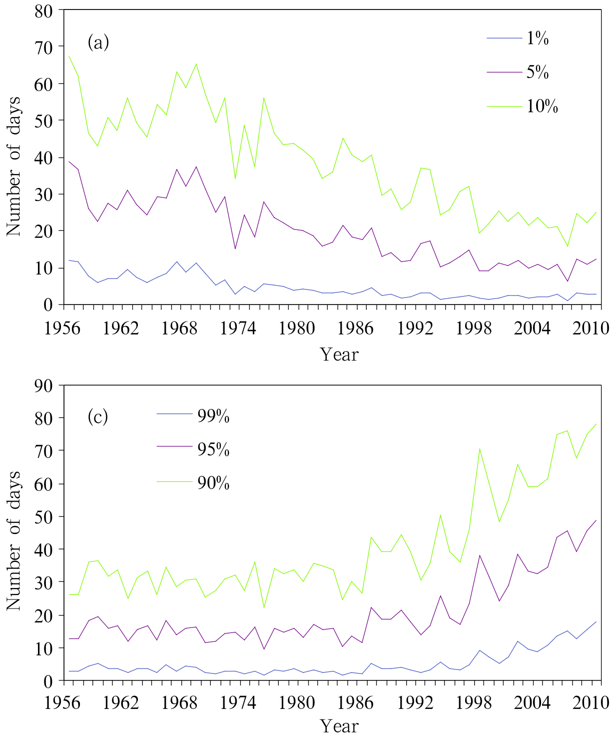

Fig. 4. Time series of annual occurrences of (a) cold nights, (b) cold days, (c) warm nights, and (d) warm days with the 10th, 5th, and 1st percentile thresholds during 1956–2010 for China.

Table 1. Comparison of the absolute and relative value of changing trends for 4 temperature extreme indices of China during 1956–2010

Threshold	Classification	Linear trend during 1956–2010			
		Warm days	Warm nights	Cold days	Cold nights
10th (90th) percentile	Absolute values (day (10 yr)$^{-1}$)	4.36*	7.80*	–2.36*	–7.57*
	Percentage (% (10 yr)$^{-1}$)	11.79*	21.00*	–6.46*	–20.64*
5th (95th) percentile	Absolute value (day (10 yr)$^{-1}$)	2.69*	4.90*	–1.34*	–4.71*
	Percentage (% (10 yr)$^{-1}$)	15.22*	27.70*	–7.71*	–27.15*
1st (99th) percentile	Absolute value (day (10 yr)$^{-1}$)	0.87*	1.68*	–0.33*	–1.51*
	Percentage (% (10 yr)$^{-1}$)	25.22*	48.14*	–9.76*	–45.21*

* denotes a result exceeding the confidence level of 5%.

correspondingly. Table 1 shows that the absolute magnitude of changing trends with the 10th (90th) percentile threshold was smaller than that with the 5th (95th) percentile threshold, and it is the same between the 5th (95th) and the 1st (99th) percentile thresholds. Actually, this comparison is not reasonable as differences of annual occurrence of extreme indices between varying intensities were great. To unify the base of comparison, the absolute trend was transformed to the relative value and expressed in percentage, divided by the climatic mean of annual numbers of corresponding indices according to intensities during 1971–2000. It is obvious that the situation reversed: the magnitude of trends with the 1st (99th) percentile threshold became the greatest, the 5th (95th) percentile threshold the second, and the 10th (90th) percentile threshold the smallest. For annual occurrence of cold nights (warm nights) with the 1st (99th) percentile threshold, its decreasing (increasing) rate was even close to half of the climatic mean per decade. That is, the more extreme the event is, the greater the magnitude of changing trends for occurrence of four temperature extreme indices is.

Second, an obvious increasing trend was observed in annual occurrence of cold days in the recent four years. A similar trend can also be found in time series of annual occurrence of cold nights but the magnitude was relatively smaller. This signal is worth being notified as a possible climatic change point.

Lastly, the magnitude of changing trends of warm extreme indices was greater than that of cold extreme indices, which is different from the conclusion of Zhou and Ren (2010), as time series were longer in the present analysis.

4.2 Spatial features

Changing trends for the 10% (90%) threshold were analyzed for each station of China. Figure 5 shows that annual numbers of cold nights (cold days) decreased during 1956–2010 at 538 (471) stations, accounting for about 94% (83%) of all stations. Changing trends of annual numbers of cold nights (cold days) were statistically significant for 91% (42%) stations of China. As pointed out by previous studies, the magnitude of decreasing trends of the annual number of cold nights was generally greater than that of cold days, with decreasing speed of –10–5 and –2.5–0 day (10 yr)$^{-1}$ for the former and latter at almost half of the total stations. For both cold nights and cold days, decreasing trends were greater in northern than southern China. Especially, in some regions such as Northeast China, North China, mid-eastern Inner Mongolia, eastern Northwest China, and western Southwest China, the annual occurrence of cold nights (cold days) decreased more than 10 (5) day (10 yr)$^{-1}$. Decreases of the annual number of cold days were not so significant in the Yangtze River valley, mid-eastern Southwest China, and South China, with even weak increasing trends being observed in some local areas.

Annual numbers of warm nights (warm days) were observed to have increased during the recent 55 years at 533 (484) stations, accounting for about 93% (85%)

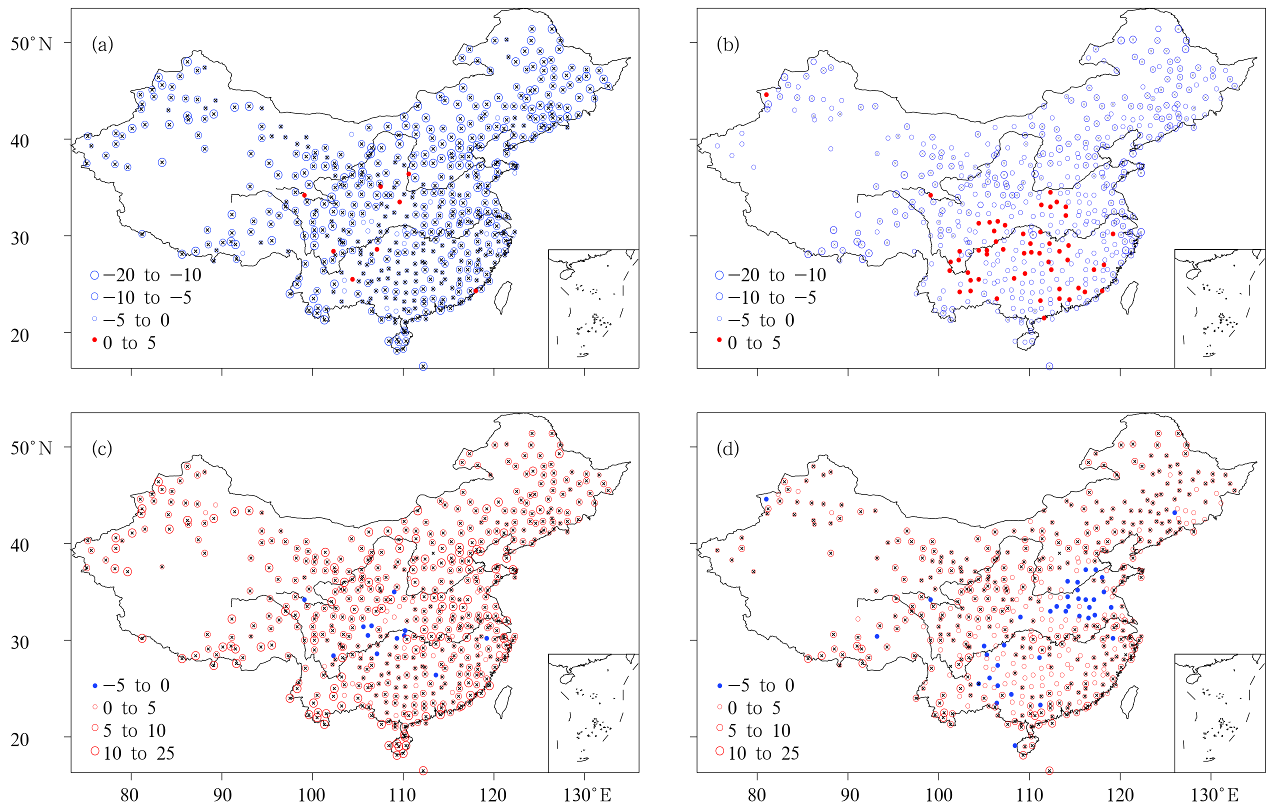

Fig. 5. Trends (day (10 yr)$^{-1}$) for annual series of the 10th percentile temperature extreme indices for 1956–2010 for (a) cold nights, (b) cold days, (c) warm nights, and (d) warm days. Trends were calculated for stations with sufficient data (at least 30-yr data during the period). The symbol × denotes a result exceeding the confidence level of 5%.

of all stations. Changing trends of annual occurrence of warm nights (warm days) were statistically significant at 89% (66%) stations of China. The magnitude of increasing trends for annual numbers of warm nights was generally greater than that of warm days. The annual number of warm nights increased at the speed of 5–10 day (10 yr)$^{-1}$ for 52% of all stations and 0–5 day (10 yr)$^{-1}$ for 21% of all stations, while the increasing rate of the annual number of warm days was smaller, 0–5 day (10 yr)$^{-1}$ for 54% of all stations. The magnitude of increasing trends was relatively smaller in eastern Southwest China and the area to the south of the mid-lower reaches of the Yangtze River for warm nights and in more extensive regions for warm days, with weak decreasing trends being observed in some parts of the region between the lower reaches of the Yellow River and the mid-lower reaches of the Yangtze River, mid-eastern Southwest China, and South China.

4.3 Seasonal features

Time series of seasonal occurrence of the four temperature extreme indices with the 10th percentile threshold are shown in Fig. 6. Obviously, interdecadal variations and trends were similar to each other between different seasons and all close to those of annual occurrence for the same index. However, numbers of both cold days and cold nights and their variability were the greatest in DJF, especially before the mid 1980s, but the least in JJA. The occurrence of warm nights and its variability were the greatest in JJA but close to each other between different seasons. Interestingly, though the occurrence of warm nights was the least in DJF, its variability was the greatest among the four seasons.

Linear trend coefficients of seasonal occurrence of the 4 temperature extreme indices with the 10th (90th) percentile threshold were calculated and presented in Table 2. Except summer cold days, changing trends of other indices were all statistically significant. Decreasing trends of both cold nights and cold days were the greatest in DJF but the least in JJA, while increasing trends of warm nights were the greatest in JJA. Trends of seasonal occurrence of the 4 tempera-

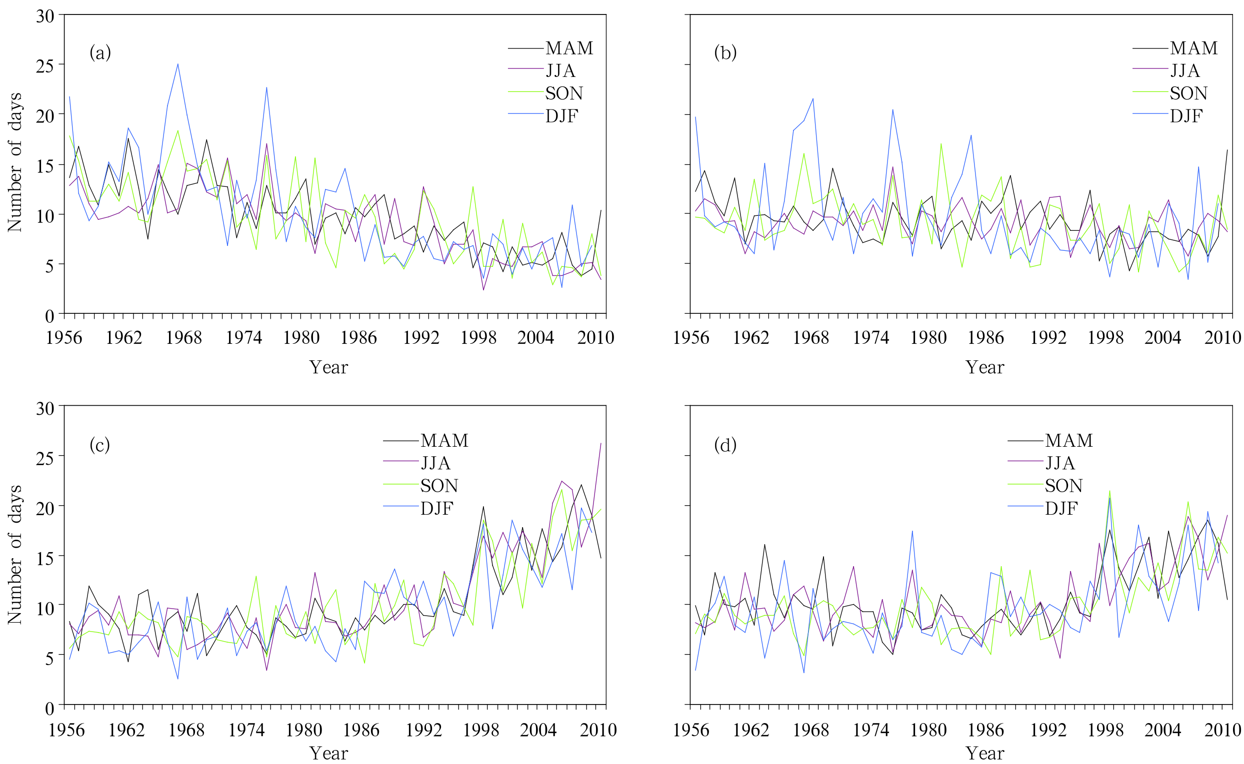

Fig. 6. Time series of seasonal occurrence of (a) cold nights, (b) cold days, (c) warm nights, and (d) warm days with the 10th percentile thresholds during 1956–2010 for China.

Table 2. Changing trends of seasonal occurrence of cold nights, cold days, warm nights, and warm days with the 10th (90th) percentile during 1956–2010

Threshold			Linear trend during 1956–2010			
			Warm days	Warm nights	Cold days	Cold nights
The 10th (90th) percentile	DJF	Absolute values (day (10 yr^{-1}))	1.11*	1.85*	–1.04*	–2.34*
		Percentage (% (10 yr^{-1}))	12.08*	19.98*	–11.40*	–25.91*
	MAM	Absolute values (day (10 yr^{-1}))	0.87*	1.74*	–0.48*	–1.71*
		Percentage (% (10 yr^{-1}))	9.41*	18.77*	–5.25*	–18.63*
	JJA	Absolute values (day (10 yr^{-1}))	1.18*	2.29*	–0.22	–1.61*
		Percentage (% (10 yr^{-1}))	12.44*	23.87*	–2.10	–17.40*
	SON	Absolute values (day (10 yr^{-1}))	1.19*	1.93*	–0.59*	–1.85*
		Percentage (% (10 yr^{-1}))	13.02*	21.07*	–6.51*	–20.44*

* denotes a result exceeding the confidence level of 5%.

ture extreme indices with the 1st (99th) and the 5th (95th) thresholds were not discussed because there were too few samples to obtain reliable results.

It is found from the above analyses that decreases (increases) of cold nights (warm nights) were more dramatic than those of cold days (warm days). This suggests that the daily minimum temperature increased more dramatically than daily maximum temperature, which has been observed and confirmed before. The high correlation between the daily minimum (maximum) temperature with annual numbers of cold nights and warm nights (cold days and warm days) suggests that significant increases of temperature may cause decreases of cold extreme indices and increases of warm extreme indices. This can also shed light on why weak or opposite trends were observed in eastern and southern parts of Southwest China, where increasing trends of mean temperature are not so significant in recent decades (Wang et al., 2004).

5. Evolution of changing trends of temperature extreme indices with varying intensities in China

Moving trends were calculated to understand the evolution of changes in annual occurrence of the four temperature extreme indices with varying intensities in China. According to the WMO standards, a time series with at least 25 years can be used to analyze a changing trend. The 25-yr moving trends were calculated in this paper, and relative trends were presented to compare the results with different intensities. In Fig. 7, each point of the curves represents the linear trend coefficient of temperature extreme indices from the 25 years before to the current year. That is, the value in 1980 indicates the trend during 1956–1980, the value in 1981 shows the trend during 1957–1981, and the rest can be deduced in the same manner. Increases of the curve indicate acceleration of decreasing trends or slowdown of increasing trends, while decreases suggest slowdown of increasing trends or acceleration of decreasing trends.

As shown in Fig. 7a, cold nights significantly decreased from 1956 to 1990, and then the decreasing trend considerably weakened. The number of cold days also decreased during the first 35 years, but maintained a relatively constant decreasing rate since 1990, and the decreasing trend showed an obvious slowdown in recent years. As for warm days and warm nights, their increasing trends have been accelerated continuously during the recent decades. Additionally, it can be noted that, the more extreme, the more intensive the acceleration (slowdown) of increasing (decreasing) trends. Especially, for annual occurrence of cold nights and cold days with the 1st percentile threshold, their current decreasing trends were much weaker than those 30 years before, and even numbers of cold days with the 1st percentile threshold showed increasing trends in the recent 4 years.

Another interesting phenomenon was observed by comparing moving trends of occurrence of temperature extreme indices between northern China and southern China, which are divided by 35°N. As shown in Fig. 8, 25-yr moving trends of occurrence of cold nights with the 10th percentile threshold for North China were similar to those for entire China (Fig. 7a), and the

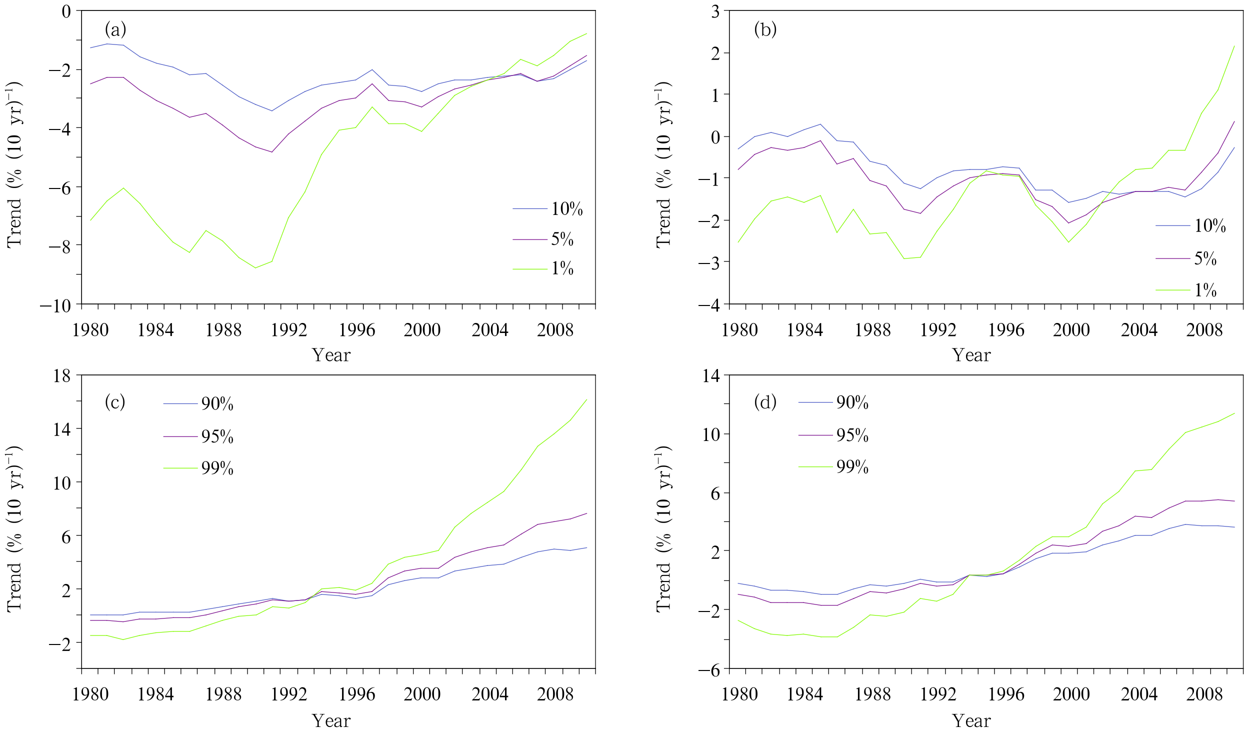

Fig. 7. 25-yr moving relative trends of annual occurrence (% (10 yr)$^{-1}$) of (a) cold nights, (b) cold days, (c) warm nights, and (d) warm days with varying intensities averaged over China during 1956–2010, with the value at 1980 being the trend during 1956–1980 and the rest being deduced by analogy.

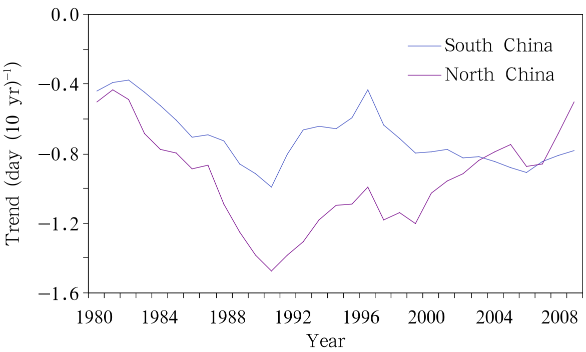

Fig. 8. 25-yr moving trends of annual occurrence of cold nights (day (10 yr)$^{-1}$) with the 10th percentile threshold averaged over North and South China.

continuous weakening of decreasing trends was significant after the 1990s. On the contrary, decreasing trends for South China did not slow down obviously in the recent 2 decades, maintaining −1 to −0.6 day (10 yr)$^{-1}$. The difference, which was mainly observed after the 1990s, suggests that changes in occurrence of cold nights in northern China are dominant. Same situations were also observed for the other three indices with varying intensities.

6. Conclusions

Using two sets of quality-controlled daily temperature observation data, with and without the inhomogeneity test and adjustment, from 654 stations of China during 1956–2004 and 1956–2010, impacts of inhomogeneity on changing trends of four types of percentile temperature extreme indices, i.e., cold days, cold nights, warm days, and warm nights with varying intensities, were discussed firstly. It is found that the inhomogeneity affected long-term trends averaged over extensive regions limitedly. After we removed 83 stations with obvious inhomogeneity impacts, from the inhomogeneous dataset, an updated analysis of changing trends of four temperature extreme indices with varying intensities during 1956–2010 was performed and the following conclusions were obtained:

(1) In addition to findings pointed out by previous studies that annual occurrences of both cold nights

and cold days decreased greatly and occurrences of warm nights and warm days increased significantly during the recent 20 years, a few new results were obtained. Firstly, the more extreme the event is, the greater the magnitude of changing trends for a temperature extreme index is. Secondly, an obvious increasing trend was observed in annual occurrences of cold days and cold nights in the recent four years. Lastly, the magnitude of changing trends of warm extreme indices was greater than that of cold extreme indices.

(2) The magnitude of changing trends was greater in northern China than in southern China. Trends for summer occurrence of cold days were not significant. Decreasing trends of occurrences of both cold nights and cold days were the greatest in DJF but the least in JJA, while increasing trends of occurrence of warm nights were the greatest in JJA.

(3) Occurrence of cold nights significantly decreased from 1956 to 1990, and then the decreasing trend considerably weakened. The decreasing trend for occurrence of cold days also showed an obvious slowdown in recent years. However, increasing trends of occurrence of both warm nights and warm days have been accelerated continuously since the recent decades. Further analysis presents that evolution of trends for occurrence of the four temperature extreme indices was dominated by changes in northern China.

It should be pointed out that many studies have discussed the impact of urbanization on trends of mean temperature (Jones et al., 1990, 2008; Zhou and Ren, 2005; Ren el al., 2008; Zhou and Ren, 2009) as well as extreme temperature indices in local regions (Zhang et al., 2011). However, urbanization is much faster in China, so the assessment of its impacts is complicated. This problem should be discussed in the future.

REFERENCES

Alexander, L. V., V. X. Zhang, T. C. Peterson, et al., 2006: Global observed changes in daily climate extremes of temperature and precipitation. *J. Geophys. Res.*, **111**, 22–31.

Bonsal, B. R., X. B. Zhang, L. A. Vincent, et al., 2001: Characteristics of daily and extreme temperature over Canada. *J. Climate*, **5**(14), 1959–1976.

Compiling Committee of China's National Assessment Report on Climate Change, 2007: *China's National Assessment Report on Climate Change.* Science Press, Beijing, 8–11. (in Chinese)

Cooter, E. J., and S. K. Leduk, 1993: Recent frost data trends in the northern United States. *Int. J. Climatol.*, **15**, 65–75.

Ding Yihui, Zhang Jin, Xu Ying, et al., 2003: *Evolution and Prediction of Climate System.* China Meteorological Press, Beijing, 4–6. (in Chinese)

Easterling, D. R., J. L. Evana, P. Y. Grosman, et al., 2000: Observed variability and trends in extreme climate events: A brief review. *Bull. Amer. Meteor. Soc.*, **81**, 417–425.

Goossens, C. H., and A. Berger, 1986: Annual and seasonal climatic variations over the Northern Hemisphere and Europe during the last centrury. *Ann. Geophys.*, **4**, 385–400.

Huang Danqing and Qian Yongfu, 2008: The definition of daily mean temperature extremes over China and its trend. *Acta Scientiarum Naturalium Universitatis Sunyatseni*, **47**(3), 112–116. (in Chinese)

—— and ——, 2009: The analysis method of regional characteristics of extreme temperature and its results. *Journal of Nanjing University (Natural Sciences)*, **45**(6), 715–723. (in Chinese)

Jones, P. D., P. Y. Groisman, M. Coughlan, et al., 1990: Assessment of urbanization effects in time series of surface air temperature over land. *Nature*, **347**, 169–172.

——, and M. Hulme, 1996: Calculating regional climatic time series for temperature and precipitation: Methods and illustrations. *Int. J. Climatol.*, **16**, 361–377.

——, D. H. Lister, and Q. Li, 2008: Urbanization effects in large-scale temperature records with an emphasis on China. *J. Geophys. Res.*, **113**, D16122, doi: 10.1029/2008JD009916.

Karl, T. R., G. Kukla, and J. Gavin, 1984: Decreasing diurnal temperature range in the Unite States and Canada from 1941–1980. *J. Climate Appl. Meteor.*, **23**, 1489–1504.

——, P. D. Jones, R. W. Knight, et al., 1993: A new perspective on recent global warming: Asymmetric trends of daily maximum and minimum temperature. *Bull. Amer. Meteor. Soc.*, **74**(6), 1007–1023.

Li Qingxiang, Liu Xiaoning, Zhang Zheng, et al., 2004: Detecting and adjusting the temporal inhomogeneity in Chinese mean surface air temperature dataset. *Adv. Atmos. Sci.*, **21**(4), 260–268. (in Chinese)

Liu Xiaoning and Li Qingxiang, 2003: Research of the inhomogeneity test of climatological data series in China. *Acta Meteor. Sinica*, **17**(4), 492–502. (in Chinese)

Ma Zhuguo, Fu Congbin, Ren Xiaobo, et al., 2003: Trend of annual extreme temperature and its relationship to regional warming in northern China. *Acta Geographica Sinica*, **58**, 11–20. (in Chinese)

Mann, H. B., 1945: Non-parametric test against trend. *Econometrika*, **13**, 245–259.

Manton, M. J., P. M. Della-Marta, M. R. Haylock, et al., 2001: Trend in extreme daily rainfall and temperature in Southeast Asia and South Pacific: 1961–1998. *Int. J. Climatol.*, **21**, 269–284.

Pan Xiaohua and Zhai Panmao, 2002: Analysis of surface air temperature extreme. *Meteor. Mon.*, **28**, 28–31. (in Chinese)

Ren Fumin and Zhai Panmao, 1998: Study on changes of China's extreme temperatures during 1951–1990. *Scientia Atmospherica Sinica*, **22**(2), 217–227. (in Chinese)

Ren Guoyu, Zhou Yaqing, Chu Ziying, et al., 2008: Urbanization effects on observed surface air temperature trends in North China. *J. Climate*, **21**, 1333–1348.

Solomon, S., D. Qin, M. Manning, et al., 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, 13.

Wei Fengying, 1999: *Diagnosis and Forecasting Methods of Modern Climatic Statistics*. China Meteorological Press, Beijing, 43–45. (in Chinese)

Wang Zunya, Ding Yihui, He Jinhai, et al., 2004: An updated analysis of the climate change in China in recent 50 years. *Acta Meteor. Sinica*, **62**(2), 228–236. (in Chinese)

—— and Ding Yihui, 2006: Climate change of the cold wave frequency of China in the last 53 years and the possible reasons. *Chinese J. Atmos. Sci.*, **30**(6), 1068–1076. (in Chinese)

Zhai Panmao and Pan Xiaohua, 2003a: Changes in extreme temperature and precipitation over northern China during the second half of the 20th century. *Acta Geographica Sinica*, **58**, 1–10. (in Chinese)

—— and ——, 2003b: Trends in temperature extremes during 1951–1999 in China. *Geophy. Res. Lett.*, **30**(17), 1913, doi: 10.1029/2003GL018004.

Zhou Yaqing and Ren Guoyu, 2005: Identifying and correcting urban bias for regional surface air temperature series of North China over period of 1961–2000. *Climatic Environ. Res.*, **10**(4), 743–753. (in Chinese)

—— and ——, 2009: The effect of urbanization on maximum, minimum temperatures and daily temperature range in North China. *Plateau Meteorology*, **28**(5), 1158–1166. (in Chinese)

—— and ——, 2010: Variation characteristics of extreme temperature indices in mainland China during 1956–2008. *Climatic Environ. Res.*, **15**(4), 405–417. (in Chinese)

Zhang Lei, Ren Guoyu, Liu Jiang, et al., 2011: Urban effect on trends of extreme temperature indices at Beijing meteorological station. *Chinese J. Geophy.*, **54**(5), 1150–1159. (in Chinese)