



**Extreme temperature
in mainland China
during 1960 to 2010**

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Changing trends and abrupt features of extreme temperature in mainland China during 1960 to 2010

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Abstract

A few researches based on the 10th (90th) percentiles as thresholds had presented to assess moderate extremes in China. However, there has been very little research reported on the occurrences of high extremes warm days (TX95p and TX99p) and cold nights (TN05p and TN01p) according to 95th or 99th (5th or 1st) percentiles which has more directly impacts on society and ecosystem systems. The study showed: (1) the frequencies of TX95p and TX99p averagely increased by 1.80 days/10 a and 0.62 days/10 a respectively in all stations of mainland China, and TX95p in 50.42 % and TX99p in 58.21 % of the stations increased significantly, but TN05p in 83.76 % and TN01p in 76.48 % of stations decreased significantly, and the frequencies of TN05p and TN01p averagely decreased by 3.18 days/10 a and 1.01 days/10 a respectively in all stations, (2) except in Central China, other regions of China showed an increasing trend in TX95p and TX99p, but vast majority of the mainland China showed a decreasing trend in TN5p and TN01p; and (3) the trends of TX95p and TX99p mutations time were in about 1990s or 2000s, but the trends of TN05p and TN01p has mutated in the late 1970s and early 1980s. After the mutation, the increasing trend of warm day and hot day is greater than before in most regions which indicated that more potential risk of heatwaves in future, but the decreasing trend of cold day and frozen day is not enlarge than before.

1 Introduction

An increase in global average temperature since the mid-20th century has been observed and the warming of the climate is unequivocal (IPCC, 2013). Global warming may have increased the frequency and intensity of the extreme weather and climate events (Alexander et al., 2006; IPCC, 2012; Habeeb et al., 2015). Compared to mean temperature increase, changing in regional temperature extremes, has more directly impacts on society and ecosystem systems (McGregor et al., 2005). Extremely hot

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summers can drastically reduce agricultural production (Asseng et al., 2011; Farooq et al., 2011), increase energy consumption (Hadley et al., 2006), and lead to hazardous health conditions (Dematte et al., 1998; Pantavou et al., 2011). Thus, understanding and predicting the spatial and temporal variability and trends of extreme weather events is crucial for the protection of socio-economic well-being, and is also crucial for understanding extreme weather events and mitigating its regional impact.

To analyze the variations in extreme climate, Expert Team of Climate Change Detection, Monitoring and Index (ETCCDMI) defined 27 extreme temperature and precipitation indices (Klein Tank et al., 2009). Two main types of extremes indices were developed by the calculation of the number of days in a year exceeding specific thresholds that have fixed values (absolute thresholds) and thresholds that are relative value (percentile thresholds) to a base period climate (Zhang et al., 2011). These indices of the number of days above or below percentile thresholds are more suitable for spatial comparisons of extremes than those based on certain absolute thresholds (Klein Tank et al., 2009). Thus, extreme temperature indexes which based on minimum temperature below the longterm 10th percentile and/or maximum temperature above the longterm 90th percentile were widely used and published in global scale, North America, South America, Europe, Asia and Australia (Alexander et al., 2006; Bonsal et al., 2001; DeGaetano and Allen, 2002; Klein Tank and Können, 2003; Zhou and Ren, 2011; Kothawale et al., 2010; Aguilar et al., 2005; Rusticucci, 2012; Nemec et al., 2013). Most of the researches based on the 10th (90th) percentiles as thresholds set to assess moderate extremes that averagely occur 36.5 times every year (10 percentage of 365 days) rather than high impact, once or twice-in-a-year weather events. Compared to moderate extremes, the high extremes temperature that based on 5th or 1st (95th or 99th) percentiles have higher potential risks on people's health and lifestyles, the economy, society, and the environment. However, there has been very little research reported on the occurrences of high extremes warm days and cold nights according to 5th or 1st (95th or 99th) percentiles.

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More than 70 % of the Earth's land area underwent a significant reduction in the number of cool nights but insignificant increase in warm days (Alexander et al., 2006). But in China, regional analyses reported that a significant reduction occurred for cool nights and a significant increase occurred for warm days (You et al., 2013; Liang et al., 2014; Wang et al., 2013; Yu and Li, 2015). Along with these regional analyses in China, the changes are much less spatially coherent even though significant trends are found in more than half of stations in the entire China mainland. Further updated studies need to amplify the spatially heterogeneous of temporal-trends on temperature extremes among different climate regions in China.

In this paper, two questions are studied in terms of temperature extreme: how the temperature extreme trends spatially distributed in different regions in mainland China; when the change point of temperature extreme trends were happened in the annual t series during 1960–2010. In this study, the 5th (95th) and 1st (99th) percentile were individually chosen to get the thresholds of 4 indices (TX95p, TX99p, TN05p, TN01p) based on the 95th and 99th percentiles of daily Tmax and at 5th and 1st of daily Tmin, respectively. The spatial heterogeneity and abrupt features of temporal-trends of the 4 indices was embodied among nine climate regions in mainland China during 1960–2010.

2 Data and methods

2.1 Data source and quality control

Daily temperature records were provided by the National Meteorological Information Center of China Meteorological Administration (CMA), including maximum and minimum surface temperature records of China from 1 January 1960 to 31 December 2010. A series of control methods were employed and the errors were corrected by the National Meteorological Information Center, which includes extreme value control and consistency check (Liu and Li, 2003; Li and Xiong, 2004). Finally, 591 stations which had

good quality data were chosen to use to analyze (Fig. 1). Data homogeneity was tested by the software RHtest V3 (<http://etccdi.pacificclimate.org/software.shtml>). In this study, no direct relationship between the year of data inhomogeneity and metadata was found and no adjustment was attempted for any stations.

2.2 Climate zones in China

The spatial heterogeneity of temporal-trends need define the climate zones in China. Based on climate zones of China that calculated by using monthly temperature and precipitation data (Zhang and Yan, 2014), considering the coincidence with administrative division of province, mainland of china was regionalized into 9 climate zones as follows (Fig. 1): Northeast China (NEC: Liaoning, Jilin, Heilongjiang), North China (NC: Beijing, Tianjin, Hebei, Shaanxi, Inner Mongolia), Northwest China (NWC: Shanxi, Gansu, Ningxia), East China (EC: Shanghai, Jiangsu, Zhejiang, Anhui, Shandong), West China (WC: Xinjiang), Southwest China (SWC: Chongqing, Sichuan, Guizhou, Yunnan), South China (SC: Guangdong, Guangxi, Hainan, Fujian), Central China (CC: Jiangxi, Henan, Hunan, Hubei) and Tibetan Plateau (TP: Xizang, Qinghai).

2.3 Extreme temperature indices

We used 5th (95th) and 1st (99th) percentile were individually chosen to get the thresholds of the 4 indices (Table 1), which is different with the indices recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI) that used 10th percentile to define the occurrences of cold nights (days) and warm days (nights). The thresholds for temperature extremes at each station are set at the 95th and 99th percentiles of daily $T_{\max}$, and at 5th and 1st of daily $T_{\min}$. According to their definitions, the temperature indices are classified cold-related indices TN05p (cold nights) and TN01p (frozen nights) and warm-related indices TX95p (warm days) and TX99p (hot days).

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2.4 Trend analysis, significance test and abrupt changes detection

Annual time-series of the indices were calculated for each station. Trends in the annual indices were calculated using linear trend estimated for each station, using all available years from 1960 to 2010. Statistical significance of the trends is evaluated at the 5 % level of significance against the null hypothesis.

The possible abrupt changes in trends of the indices have been examined by using Mann–Kendall method and 5 yr moving T test (MTT) method (Alexander et al., 2006). For the emergence of multiple point mutations after using Mann–Kendall method, the 5 yr moving T test method were used to verify the authenticity of the mutation point to enhance the credibility of the results (Klein Tank and Können, 2003; Wei, 2007).

3 Results

3.1 Trends of temperature extreme

This section gives an overview of time series for 4 temperature extreme indices averaged by all the stations in mainland of China (Fig. 2). Figure 3 summarizes the results of anomalies in annual temperature extreme indices averaged by all the stations in mainland of China. The warm days (TX95p) and hot days (TX99p) days underwent increase trends in recent 51 years, with a linear trend +1.8 day/10 a and linear trend +0.62 day/10, respectively; and the cold nights (TN05p) and frozen nights (TN01p) showed downward trends with a linear trend −3.18 day/10 a and linear trend −1.01 day/10 a, respectively (Fig. 2). Both warm days and hot days days showed rapid increases trends after mid-1980s although slight decrease tendencies appeared before mid-1980s, and cold nights and frozen nights almost followed downward trends despite a short-term upward trend before 1970s (Fig. 3).

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3.2 Spatial variations of trends in extreme temperature

This section showed the trends' spatial variations of 4 indices in mainland China (Fig. 4) AND the stations' percentage of trends and passed the significant test ($P < 0.05$) among 9 climate zones (Table 2).

3.2.1 Trends' spatial distributions of 4 indices among China

TX99p and trends TX95p have similar spatial patterns, although the trend values may be different, and the TX95P and TX99P showed an increasing trend in almost all the regions of mainland but Central China (CC) and its surrounding areas where presented a decreasing trend or insignificant trends (Fig. 4a and b). Except the junction area of North and Northwest China (NC and NWC), the northwest of Southwest China (SWC), and a few sites in northeast of East China (EC), most of the site was to reduce TN05p and TN01p trend (Fig. 4c and d). Both the largest increases in TX95P and TX99P frequency, and biggest decreases in TN05p and TN01p, are mostly located in similar regions in NC, NWC, WC, TP, SWC, SC north of CC, WC, especially in up reaches of Yellow River and Yangtze River, and estuary of Yangtze River.

3.2.2 Spatial variations of significantly trends for 4 indices in China

TX95p and TX99p in more than half of the stations increased significantly, and TN05p and TN01p in more than three-quarters of stations decreased significantly (Table 2). In mainland China, more than half of the stations were significantly increasing trends in TX95p and TX99p (50.42 and 58.21 %, respectively), and 83.76 % stations of TN05p and 76.48 % stations of TN01p showed significantly downward tendencies. The percentages of significantly decrease sites in TX95p and TX99p were 3.38 and 4.74 % respectively, and significantly increase sites in TN05p and TN01p were 0.85 and 1.18 % respectively.



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Except for CC where only 8.7 % stations in TX95p and 18.84 % stations in TX99p significantly increased but 11.59 % stations in TX95p and 36.23 % stations in TX99p significantly decreased, 30–75 % stations had significantly increase tendency and less than 10 % stations had significantly decrease trends among the other 8 climate zones (Table 2). More than 80 % stations in TN05p among the other 8 climate zones significantly decrease except for TP where only 39.36 % stations in TN05p significantly declined, and more than 80 % stations in TN01p among the climate zones would significantly decrease if Not including TP, NEC and EC.

3.3 Characteristics of mutation in TX95p and TX99p trends

The mutation in TX95p and TX99p trends were mainly in 1990s and 2000s (Table 3). The abrupt changes in trends of TX95p early occurred in the 1980s in NEC and CC, and latest occurred in the 2000s in the SWC, SC and EC, and mutations in the 1990s was NC, TP, WC and NWC. The TX99p mutation early occurred in SC and CC in the mid-1980s and latest occurred in the 2000s in the NEC and SWC and EC, and the observed abrupt changes in the 1990s was NC, TP, WC and NWC (Table 3).

All the trends values of TX99p among the climate zones after mutation were bigger than before mutation, but the trends values of TX9p in more than half the number of climate zones (NEC, NC, WC, NWC and EC) after mutation were bigger than before mutation (Table 3).

3.4 Characteristics of mutation in TN05p and TN01p trends

Except for TP that mutation of TN05p occurred in 2001, other climate zones' mutation of TN05p and TN01p occurred in the 1980s and the end of 1970s (Table 4). The decreasing trends of TN01p among the climate zones after mutation were shrunk than before mutation except for WC, but the decreasing trends of TN05p in more than half the number of climate zones (NC, TP, SC, NWC and EC) after mutation were shrunk than before mutation (Table 4).

4 Discussion

The last IPCC report points out that there is an increasing concern about temperature extremes, which are expected to be more frequent (IPCC, 2012). In mainland China, this study showed that the frequencies of TX95p and TX99p averagely increased by 1.80 days/10a and 0.62 days/10a respectively, and the frequencies of TN05p and TN01p averagely decreased by 3.18 days/10a and 1.01 days/10a respectively, and Zhou and Ren (2011) show a increase at a rate of 5.22 days/10a occurred for warm days (TX90p) and a reduction at a rate of -8.23 days/10a occurred for cool nights (TN90p) during 1961–2008. The increase rates of warm days in 90th, 95th and 99th percentiles are much less than the decrease rates of cold nights in 10th, 5th and 1st percentiles, respectively, which seems to be associated with asymmetric warming characteristic that the rate of increase in daily minimum temperature is significantly higher than that of daily maximum temperature (Easterling et al., 1997; Karl et al., 1993; Vose et al., 2005). More warm days increase and less cold nights were also detected in different seasons or subareas of China (You et al., 2013; Li et al., 2010; Zhai and Pan, 2003; Shi and Cui, 2012). The increase (decrease) of warm days (cold nights) whether 90th (10th), 95th (5th) or 99th (1st) percentiles in China are consistent with all other global or regional studies that shown that the occurrence of warm days increased, but cold days decreased (Bonsal et al., 2001; DeGaetano and Allen, 2002; Klein Tank and Können, 2003; Alexander et al., 2006).

This study showed the frequency of warm and hot days was an increasing trend but the cold and frozen days was a decreasing tendency in almost everywhere except for Central China and its surrounding areas where the warm and hot days tended to decrease. In Central China, T_{max} or warm days in summer shows a cooling trend also were found by Qi and Wang (2012) and (You et al., 2013). The trends of TX95p and TX99p mutations time were in about 1990s or 2000s but the trends of TN05p and TN01p has mutated in the early and mid 1980s. The similar mutations time were detected by Qi and Wang (2012), and the trends in East Asia was found reverse after 1997 (Li et al.,

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2012). The research showed that after the mutation, the increasing rate of warm days and hot days is much greater than before in most areas of China. And extreme warm days (with daily maximum temperature $> 35^{\circ}\text{C}$) increased significantly in most of China during 1961–2007 (Ding et al., 2010). Ensemble multi-model projected more extreme
5 warm events and less cold events are expected over China in future under the RCP4.5 scenario (Yao et al., 2012). All these indicated that more potential risk of heatwaves in future, which not only affects human health and disease but also can change the probability of agrometeorological disasters. However, crops' growth duration was shortened, as well as the sowing date or the phenology was shifted because of climate warming
10 (Fang et al., 2015, 2013; Richardson et al., 2013), limited knowledge in crops response to climate warming and deserve more attention in the future.

5 Conclusions

1. It is showed that warm days and hot days underwent an increase trend in recent 51 years, and a rapid increase after mid-1980s. The cold days and frozen days underwent a decrease trend in recent 51 years, and a rapid decrease from 1960s to 1990s.
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2. The warm days (cold days) and hot days (frozen days) showed an upward (downward) tendency in most area of China, but Central China and its surrounding areas showed an decline tendency in warm days and hot days.
- 20 3. The trends of warm days and hot days mutations time were in about 1990s or 2000s, but the trends of cold days and hot days has mutated in the early and mid 1980s. The increasing trend of warm day and hot day is greater after the mutation in most regions, which indicated that more potential risk of heatwaves in future.

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Table 1. Definition of 4 temperature indices in China.

Name	Index	Definition
Warm days	TX95p	Count of days where maximum temperature TX > 95th percentile
Hot days	TX99p	Count of days where maximum temperature TX > 99th percentile
Cold nights	TN05p	Count of days where minimum temperature TN < 5th percentile
Frozen nights	TN01p	Count of days where minimum temperature TN < 1st percentile

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Table 2. The percentage of stations which had increase and decrease trends and passed the significant test ($P < 0.05$) among 9 climate zones in mainland of China.

	TX95p		TX99p		TN05p		TN01p	
	Increase (%)	Decrease (%)	Increase (%)	Decrease (%)	Increase (%)	Decrease (%)	Increase (%)	Decrease (%)
Mainland China	50.42	3.38	58.21	4.74	0.85	83.76	1.18	76.48
NEC (Northeast China)	37.50	0	43.06	0	1.39	86.11	1.39	37.5
NC (North China)	68.67	1.20	72.29	1.20	1.20	87.95	1.20	91.57
SWC (Southwest China)	48.89	3.33	51.11	4.44	1.11	80.00	0	100
TP (Tibetan Plateau)	40.43	0	44.68	0	2.13	39.36	0	18.09
WC (West China)	51.02	6.12	48.98	4.08	0	81.63	8.16	91.84
SC (South China)	65.33	4.00	58.67	2.67	0	82.67	0	100
NWC (Northwest China)	66.67	1.96	74.51	0	0	80.39	0	80.39
CC (Central China)	8.70	11.59	18.84	36.23	0	79.71	0	78.26
EC (East China)	32.73	1.82	32.73	7.27	0	96.36	1.82	49.09

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Table 3. Mutation years, trends before and after the mutation in TX95p and TX99p.

	Year of abrupt change		Trends (days/10 a) Before and after abrupt change			
	TX95p	TX99p	TX95p		TX99p	
			before	after	before	after
NEC	1981	2001	0.7	2.9	0.9	0.4
NC	1995	1996	−0.9	1.8	−0.4	−1.0
SWC	2003	2001	0.45	12.1	0.1	5.3
TP	1992	1993	1.3	6.5	0.2	2.0
WC	1994	1996	−0.05	0.74	0.04	−0.28
SC	2000	1985	1.08	10.2	−0.5	1.7
NWC	1995	1997	−0.68	1.2	0.2	0.1
CC	1987	1987	−4.7	4.1	−1.7	1.1
EC	2000	2001	−0.07	0.27	−0.2	−1.1

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Table 4. Mutation years, trends before and after the mutation in TN05p and TN01p.

	Year of abrupt change		Trends (days/10 a) Before and after abrupt change			
	TN05p	TN01p	TN05p		TN01p	
			before	after	before	after
NEC	1980	1976	−0.9	−1.7	−2.5	−1.2
NC	1980	1981	−2.6	−2.1	−1.0	−0.1
SWC	1985	1986	−0.7	−2.1	−0.7	−0.4
TP	2001	1986	−3.4	−2.7	−1.7	−1.0
WC	1980	1979	0.003	−1.2	0.67	−0.2
SC	1979	1985	−2.6	−2.3	−0.5	−0.2
NWC	1980	1981	−1.8	−1.1	−0.4	0.2
CC	1984	1980	0.23	−0.07	−0.5	−0.3
EC	1985	1983	−0.59	−0.05	−1.0	−0.6

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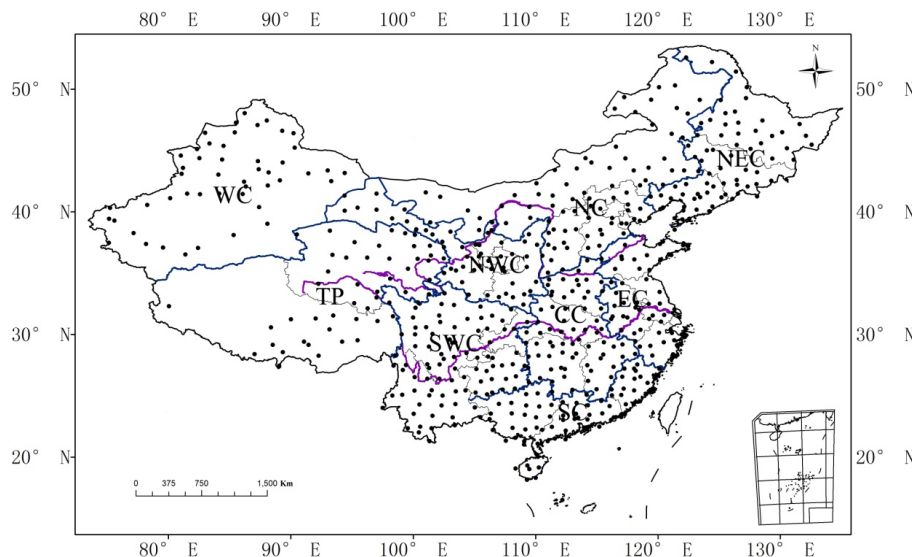


Figure 1. Distribution of the weather stations and climate zones. The up purple curve lines is the Yellow River and the down purple curve lines is Yangtze River. The blue line is used to separate the different climate zones.

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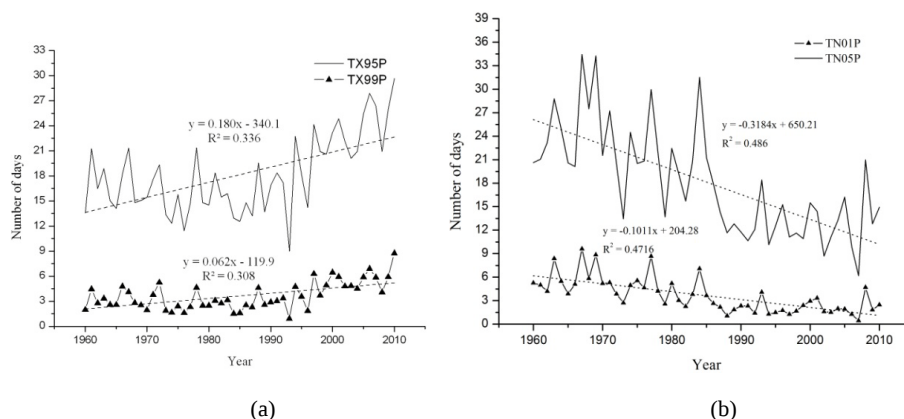


Figure 2. Time series of annual occurrences of warm days (TX95p), hot days (TX99p), cold nights (TN05p) and frozen night (TN01p) in mainland China during 1956–2010. **(a)** Warm days (TX95p) is the lines of up and hot days (TX99p) is the lines of down; **(b)** warm days (TN05p) is the lines of up and hot days (TN01p) is the lines of down. The dashed lines are linear trends, and all the linear trends are statistically significant at p value < 0.05 .

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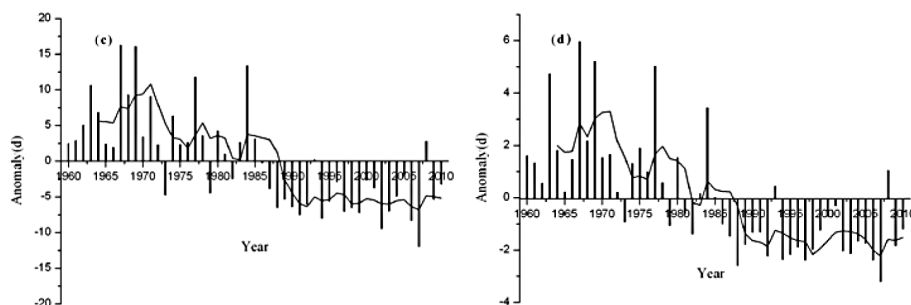


Figure 3. Anomalies in annual (a) warm days (TX95p), (b) hot days (TX99p), (c) cold days (TN05p) and (d) frozen days (TN01p) averaged by all the stations in mainland of China during 1960–2010. The anomalies are relative to 1971–2000 mean values. The Curve fitting used a 5a moving average smoothing method.

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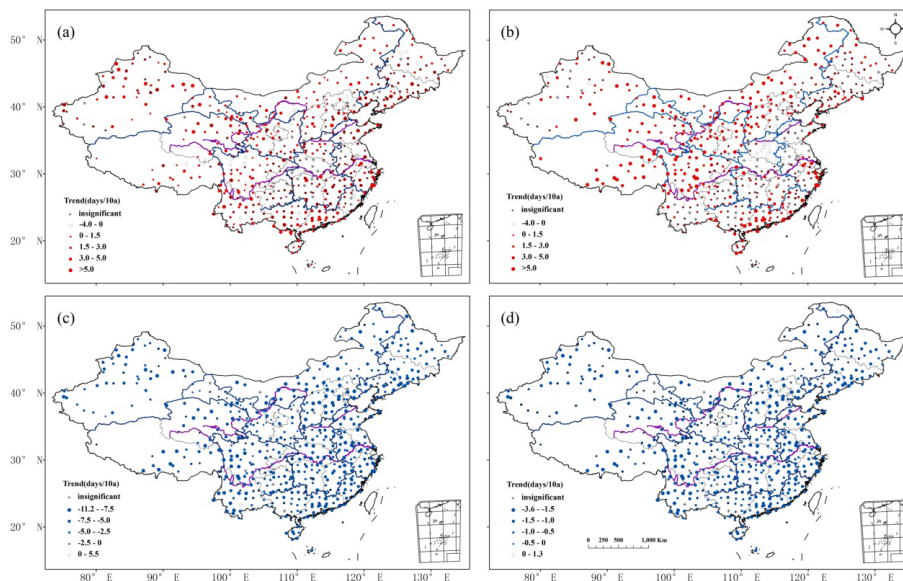


Figure 4. Trends' spatial distributions of temperature extreme indices among China during 1960–2010: **(a)** trends of TX95p; **(b)** trends of TX99p; **(c)** trends of t TN05p; **(d)** trends of TN01p. The black symbol “+” showed the stations whose trends were insignificant at the confidence level of 0.05. The no color filled symbol “o” represent increased frequency in TX95p and TX99p, and decreased frequency in TN05p and TN01p.

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