Urbanization Effect on Trends of Extreme Temperature Indices of National Stations over Mainland China, 1961–2008

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ABSTRACT

Understanding the long-term change of extreme temperature events is important to the detection and attribution of climate change. It is unclear, however, how much effect urbanization has had on trends of the extreme temperature indices series constructed based on the commonly used datasets on a subcontinental scale. Applying a homogenized daily temperature dataset of the national reference climate stations and basic meteorological stations, and a rural station network previously developed, urbanization effects on trends of extreme temperature indices in mainland China for the time period 1961–2008 are evaluated. It is found that 1) the country-averaged annual- and seasonal-mean extreme temperature indices series generally experience statistically significant trends; 2) annual-mean urbanization effects in the country as a whole are statistically significant for daily minimum temperature (Tmin), maximum temperature (Tmax), and mean temperature of Tmin and Tmax (Tavg), reaching 0.070°, 0.023°, and 0.047°C $(10\,\mathrm{yr})^{-1}$, respectively, with the largest values for annual-mean Tmin occurring in north China; 3) annual- and seasonal-mean urbanization effects for the declining diurnal temperature range (DTR) are highly significant, and the largest seasonal-mean DTR decline because of urbanization occurs in winter and spring; 4) annual-mean urbanization effects for the lowest Tmin, summer days, tropical nights, and frost days series are significant, but an insignificant urbanization effect is detected for icing days series; 5) urbanization has led to a highly significant decline of annual cold nights at a rate of -1.485 days $(10\,\mathrm{yr})^{-1}$ and a highly significant increase of annual warm nights at a rate of 2.264 days $(10\,\mathrm{yr})^{-1}$. Although urbanization effects are also significant for cold days and warm days, they are relatively smaller, and 6) the smallest absolute values of annual-mean urbanization effects for most of the indices series are found to dominantly appear during 1966–76, a well-known deurbanization period resulting from the Cultural Revolution.

1. Introduction

An understanding of long-term change of extreme temperature events is of importance to the detection and attribution of climate change and to the assessment of climate change impacts on natural and human systems. It is unclear in the present, however, whether or to what extent the urbanization has affected the long-term trends of the extreme temperature indices series constructed based on the frequently used observational datasets on a subcontinental to global scale.

Many studies on changes in extreme climate events were conducted in the past decade, and almost all of them showed coherent changes in the temperature indices series over the post-1950 time periods in the continents or countries, with the warm extreme temperature indices witnessing significant increasing trends and cold extreme temperature indices witnessing significant decreasing trends (Easterling et al. 2000; Frich et al. 2002; Alexander et al. 2006; Ding et al. 2006; Solomon et al. 2007; Peterson et al. 2008; Choi et al. 2009; Shi et al. 2009; Zhou and Ren 2011; Ren et al. 2011; L. Zhang et al. 2011). Alexander et al. (2006) showed significant changes in temperature extremes associated with climate warming from 1951 to 2003, for example, indicating that more than 70% of the global land area underwent a significant decrease in frequency of cool nights and

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a significant increase in frequency of warm nights. Klein Tank and Konnen (2003), Vincent et al. (2005), and Choi et al. (2009), respectively, reported the similar long-term changes in extreme temperature indices in Europe, South America, and the Asian–Pacific region.

Studies for mainland China also evidenced the countrywide reduction in frequency of cold waves, frost days, and cool days (nights) and a general increase in frequency of hot events and warm days (nights), though some differences still existed among the trend estimates because of the varied time periods, areas analyzed, and the different criteria used (Yan el al. 2002; Zhai and Pan 2003; Ma et al. 2003; Qian and Lin 2004; Gong and Han 2004; Liu et al. 2006; You et al. 2008). Recently, Zhou and Ren (2011) updated the analysis of spatial and temporal changes in extreme temperature events in mainland China based on a homogeneity-adjusted daily temperature dataset of 526 stations for period 1961–2008, showing that, across the country, frost days and ice days significantly reduced and annual highest daily maximum temperature (Tmax) and daily minimum temperature (Tmin) (TXX and TNX) and annual lowest Tmax and Tmin (TXN and TNN) generally rose. The analysis also found that cool nights (days) significantly decreased at a rate of $-8.23\,\mathrm{days}\,(10\,\mathrm{yr})^{-1}$ [$-3.26\,\mathrm{days}\,(10\,\mathrm{yr})^{-1}$], and warm nights (days) significantly increased at a rate of $8.16\,\mathrm{days}\,(10\,\mathrm{yr})^{-1}$ [$5.22\,\mathrm{days}\,(10\,\mathrm{yr})^{-1}$] in the country as a whole. These latest results are generally consistent with those reported in the previous studies for mainland China except for the slightly higher estimates mainly due to updated data series.

An important issue in the studies, however, is whether or not, or to what extent, the urban warming near the weather stations has affected the estimates of trends of the extreme temperature indices on a large spatial scale. Many studies for mainland China and other eastern Asian countries in the past decade have evidenced the significant urbanization effect on area-averaged annual- and seasonal-mean surface air temperature (SAT) trends over the post-1950 periods as estimated from the commonly applied observational datasets (e.g., Zhao 1991; Choi et al. 2003; Kalnay and Cai 2003; Zhou et al. 2004; Chung et al. 2004; Ren et al. 2005, 2008; Chen et al. 2005; Tang et al. 2008; Fujibe 2009; Zhang et al. 2010; Yang et al. 2011, 2012; Wu and Yang 2013; He et al. 2013; Li et al. 2013). A recent and comprehensive study by Zhang et al. (2010) used data from all of the weather stations for selecting reference stations to evaluate the urbanization effect on SAT trends in mainland China, and they showed that, in the warming trend of annual-mean SAT estimated based on the dataset of national Reference Climatic and Basic Meteorological Stations (RCBMS or National Stations hereafter) in 1961–2004, annual-mean urban warming ranged mostly among $0.06°$–$0.09°\mathrm{C}\,(10\,\mathrm{yr})^{-1}$, contributing 27% to the overall warming over the country as a whole. The urban heat island (UHI) effect therefore had a significant effect on the increasing SAT trends of the country as estimated by the observational records from the RCBMS. Since the enhanced UHI magnitude has obviously contributed to the overall increasing trends of mean SAT in mainland China, it must have exerted some influence on trends of Tmax and Tmin and the trends of the extreme temperature indices series based on the Tmax and Tmin as well.

Chen et al. (2005) analyzed the urbanization effect on area-averaged Tmax and Tmin trends in Hubei Province, central China, for the time period 1960–2004 and showed a large proportion of urban warming in annual- and seasonal-mean Tmin trends. Similar results were reported by Hua et al. (2008) for mainland China and by Zhou and Ren (2009) for north China, with the latter indicating a 53% contribution of urbanization to the long-term trend of annual-mean Tmin during 1961–2000. L. Zhang et al. (2011) and Zhou and Ren (2011) were among the first studies to further evaluate the urbanization effect on long-term trends of the commonly applied extreme temperature indices in Beijing Municipality and north China, and they all reported significant urbanization effects on the indices series related to daily Tmin including frost days, cold nights, warm nights, the lowest and highest Tmin, and diurnal temperature range (DTR). The urbanization effects on the negative trends of frost days, DTR, cool nights, and cool days, and the positive trends of summer days, tropical nights, TNX, TNN, and warm nights calculated based on the data of RCBMS for the time period 1961–2008 in north China were all statistically significant at the 0.05 confidence level (Zhou and Ren 2011).

It is unclear at present, however, how much effect the rapid urbanization, especially the increased UHI magnitudes, has had on the long-term trends of the extreme temperature indices series of the RCBMS in mainland China as a whole. The RCBMS dataset has been frequently used by researchers in China for analyzing the long-tern changes in mean and extreme climate (Ren et al. 2008, 2012), and it is desirable to identify the nature and extent of the urbanization contribution in the dataset after the urbanization effect on trends of regional-averaged annual- and seasonal-mean temperature series in mainland China has been well understood. In this paper, we apply a homogeneity-adjusted daily temperature dataset and a reference SAT network previously developed by Ren et al. (2010b) to evaluate the urbanization effects on trends of the extreme temperature indices in mainland China. Our investigation shows a similarly significant urbanization effect across the country,

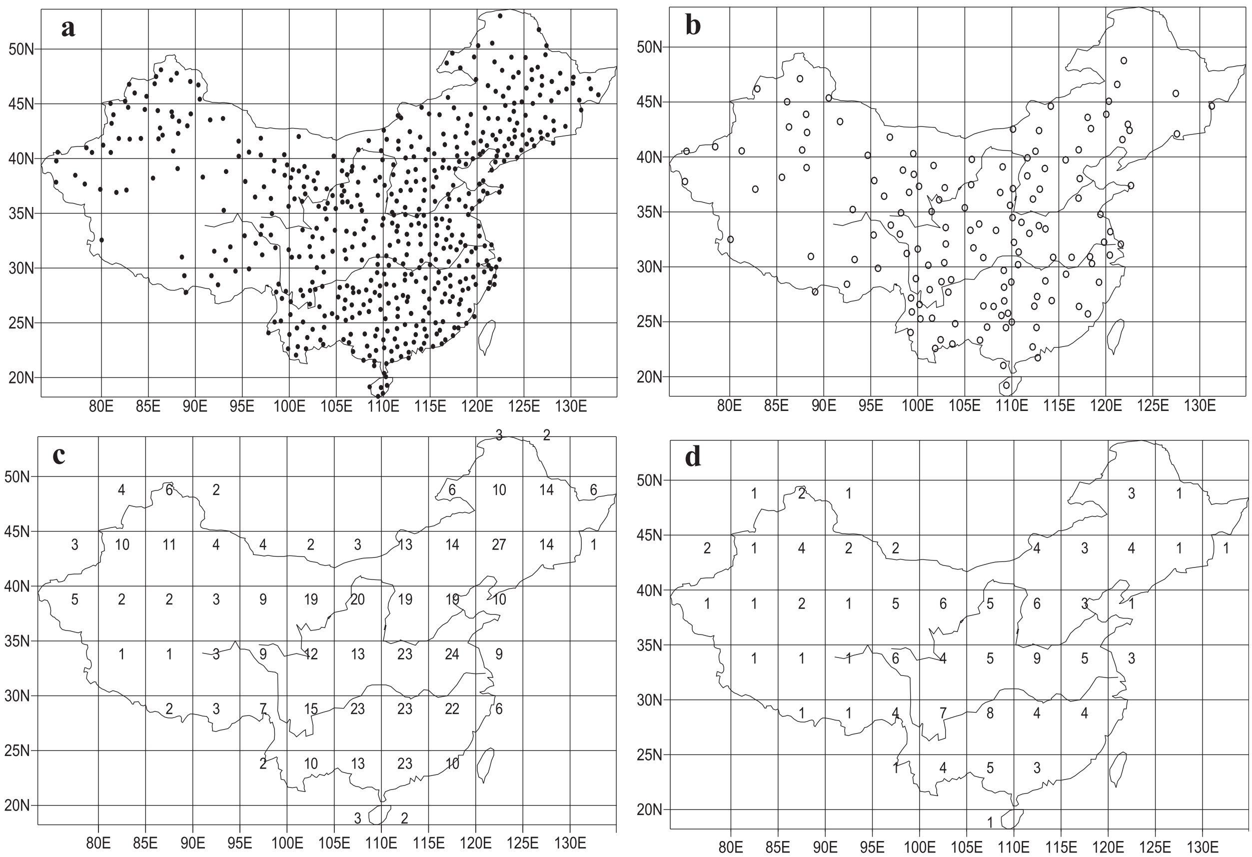


FIG. 1. Distribution of the (a) RCBMS and the (b) reference/rural stations in mainland China, and the numbers of stations within the 5° × 5° latitude–longitude grids for the (c) RCBMS and the (d) reference/rural stations.

despite the effect being somewhat smaller in magnitude than that found for north China.

2. Data and methods

a. Selection of reference temperature stations

It is crucial to have a set of representatively rural stations for evaluating the urbanization effect on trends of SAT and the related extreme indices series (Hansen et al. 2001; Pielke et al. 2007; Ren et al. 2008). Ren et al. (2010b) developed a rural/reference temperature station (reference station hereafter) network for use in studies of urbanization effect on SAT in mainland China, applying a comprehensive procedure and all the available weather stations of approximately 2300. The procedure took a consideration of spatial distribution and density of stations, length and complicity of records, times and distance of relocations, population in the nearby cities/towns, proportion of built-up areas around the stations (within 12 km^2 around the observational grounds), and straight distance from the center of the cities and towns. For example, the population in the built-up areas of the cities and towns where the stations are located must be less than 20 000 in central and western China and be less than 70 000 for 16 provinces (municipalities) in the eastern plain areas of China; station relocations must occur no more than two times since 1961, and the relocation distance must be within 5 km; and the percentage of the built-up areas within a radius of 2 km (or within about 12 km^2) around the observational grounds must be less 33%. These criteria were forged and adopted to account for the different influences on SAT observations from local anthropogenic activities in varied spatial scales. A detailed description of the procedure for selecting the reference stations was given in Ren et al. (2010b), and a brief introduction to the comprehensive method and the comparison with that of remote sensing–based land surface brightness temperature were also given in Ren and Ren (2011).

A total of 143 stations were finally chosen by applying the procedure (Fig. 1), among which 68 are from the RCBMS managed by the China Meteorological Administration (CMA), and 75 are from the Ordinary Meteorological Stations (OMS) previously overseen by provincial meteorological bureaus but now are also overseen by the CMA. We used 141 reference stations of the network because the records from 2 stations have not been updated. A brief description of the RCBMS and OMS including how they are used for climatic researches in mainland China is given in section 2b.

Overall, the reference stations are well spatially distributed, though they are still relatively smaller in number in northern northeast China, northwest China, and the western Qinghai–Tibetan Plateau. As an example, the grid where northern Beijing City is located contains three reference stations (Figs. 1b,d): Shangdianzi, Beijing; Gangzi, Inner Mongolia; and Linxi, Inner Mongolia. An OMS, Shangdianzi station is located on a hill slope at an elevation of 287 m above mean sea level (MSL), and it is near a mountain village with a population less than 9000 in 2000; Gangzi station is also an OMS, but Linxi station is one of the RCBMS, and both are located in the Inner Mongolian Plateau with elevations 961 and 800 m MSL, respectively, and a population of 9200 and 11 000, respectively, in 2000. This station network was compared to another reference network of 138 stations developed by using the surface brightness temperature data retrieved from the remote sensing of satellite, and it was found to have similar country-averaged trends of annual- and seasonal-mean SAT and the magnitudes of urban warming of the RCBMS for the same time periods (Ren and Ren 2011). It has been applied already for identifying and adjusting the urban biases of mean SAT of the RCBMS in mainland China (Zhang et al. 2010; Zhou and Ren 2011). In this study, we use the daily temperature data of the reference station network for examining urbanization effects on an extreme temperature indices series in mainland China.

b. *Data and processing*

Daily temperature data are from the National Meteorological Information Center (NMIC) of the CMA. There are different historical datasets available in the CMA for use in studies of climate change, but the most frequently applied historical SAT dataset has been the observational records from the RCBMS, consisting of about 730 stations approximately evenly distributed across the country but more located near cities and towns. As a subset of the dataset, the national Reference Climate Stations (RCS) consisting of 143 stations (160 stations for a variant in some publications) more evenly distributed spatially and nearer big cities have also been used by climatologists. The readings at the RCS were made 24 times a day before the application of the autonomous weather station (AWS) system around 2004 in mainland China. Another subset of the dataset is the national Basic Meteorological Stations (BMS, about 580 stations), manually observed eight times a day before the AWS system, also mostly situated near cities or towns (Ren et al. 2008; Zhang and Xu 2008). In the last decade, the historical temperature records of the RCS and BMS were merged and inhomogeneity-adjusted to meet the increasing demand for climate change studies (Li et al. 2004; Ren et al. 2005, 2012; Ding et al. 2006). The RCBMS include almost all the stations with long-term records in mega and large cities of mainland China, and few are really located in rural areas. In addition, there are about 1600 OMS that are mostly located near small cities, towns, and villages, but the observations were manually made only three times (0800, 1400, and 2000 local time) a day before about 2004, and they have been seldom applied so far in large-scale analyses of climate change.

The objective of this study is to investigate into the nature and magnitude of the urbanization effect on the estimates of trends of the commonly used extreme temperature indices obtained from data of all the RCBMS. These stations are regarded as problematic ones in this work, as evidenced in many previous studies, and they are to be evaluated in terms of the systematic bias of mean SAT and extreme temperature indices series induced by urbanization. The urbanization effect may result from a complex matrix of influential factors including poor siting on the microscale, urban heat island effect, enhanced precipitation in or near built-up areas, and increased concentration of atmospheric aerosols in the urban boundary layer. For example, most of these stations are characterized by being too close to the built-up areas of cities and the poor siting or deteriorative microsettings immediately around the observational grounds. The unqualified microsettings are one of the many problems related to urbanization. One of the more important issues in addition to the poor microsettings would be the enhanced urban island intensity near the observational sites that is more associated with the size and population of the cities where the stations are located. By applying the ''good'' reference stations, as described in section 2a, we could evaluate the overall urbanization effect on the trends of the extreme temperature indices series at the ''poor'' RCBMS.

Daily temperature data of 1951–2004 from the RCBMS were inhomogeneity-adjusted by the NMIC (Li et al. 2004). The method of Easterling and Peterson (1995) was adopted to conduct the detection and adjustment of the inhomogeneities of the monthly-mean data, and the monthly average adjustments were then applied to daily records to obtain the homogenized daily temperature data. The discontinuous points mainly caused by relocations had been adjusted to the latest observational locations, and the historical SAT records from the 730 stations can be considered as being relatively homogenous after the adjustments (Li et al. 2004;

TABLE 1. Extreme temperature indices used in this study [modified from Zhang and Yang (2004) and Zhou and Ren (2011)].

Category	Abbreviation	Term	Definition (unit)
Mean and extreme value	TN	Tmin	Mean value of daily Tmin (°C)
	TX	Tmax	Mean value of daily Tmax (°C)
	TM	Tavg	Mean value of Tmax and Tmin (°C)
	DTR	Diurnal temperature range	Difference between Tmax and Tmin (°C)
	TNX	Highest Tmin	Monthly maximum value of Tmin (°C)
	TXX	Highest Tmax	Monthly maximum value of Tmax (°C)
	TNN	Lowest Tmin	Monthly minimum value of Tmin (°C)
	TXN	Lowest Tmax	Monthly minimum value of Tmax (°C)
Absolute threshold	FD0	Frost days	Annual count when daily Tmin < 0°C (day)
	SU25	Summer days	Annual count when daily Tmax > 25°C (day)
	ID0	Icing days	Annual count when daily Tmax < 0°C (day)
	TR20	Tropical nights	Annual count when daily Tmin > 20°C (day)
Relative threshold	TN10p	Cool nights	Days when daily Tmin < 10th percentile (day)
	TX10p	Cool days	Days when daily Tmax < 10th percentile (day)
	TN90p	Warm nights	Days when daily Tmin > 90th percentile (day)
	TX90p	Warm days	Days when daily Tmax > 90th percentile (day)

Li and Dong 2009). The homogenized monthly and daily SAT datasets have been frequently used in studies and services of regional climate change in China (Ren et al. 2005, 2012; Tang et al. 2005; Ding et al. 2006; You et al. 2012). We update the data to 2008, and the after 2004 records are simply connected to the adjusted data series, with an assumption that the inhomogeneities in the last 4 yr are negligible. The assumption is somehow debatable because although the relocations might have little influence, the nationwide applications of the AWS around 2004 might have caused some discontinuities in the daily temperature records. However, Wang et al. (2007) compared the country-averaged annual- and seasonal-mean SAT of the AWSs with those of the manual observations and found an insignificant difference, despite the fact that the maximum (minimum) temperature of the AWSs somehow exhibits systematically higher (lower) values in the country as a whole.

Among the records of 74 stations of the OMS in the reference station network, which had already been quality controlled by the NMIC, only nine with annual-mean SAT series are found to be inhomogeneous due to the moves of observational locations, and the monthly and daily temperature data of the nine stations are therefore adjusted by using the same method as that used by Li et al. (2004) for the data of the RCBMS. The significant inhomogeneities have not been found or verified for the SAT data series from the other OMS sites, and they are assumed as homogeneous and, together with the adjusted data, are simply merged with the RCBMS data of the reference station network for use in this study.

Most of the stations actually started routine observations after the mid-to-late 1950s, and there also existed missing records in the entire data series of some stations. We take 1961 as the beginning year and choose those stations with records suffering from missing values less than 2% of the total days of 1961–2008 for the analysis. The records of 526 stations in the RCBMS dataset can meet the requirement (Fig. 1). It is clear from Fig. 1 that the stations selected for use in this study are approximately evenly distributed across the country, despite observations in the northwestern deserts and western Tibetan Plateau still being small in number due to the lack of weather stations.

Finally, we recheck the quality of the daily SAT data of all stations used with RClimDex software developed by Zhang and Yang (2004) and find that 10 records from six stations are not reasonable with the temperature values larger than 4 times that of standard deviations of the data series. These wrong records are treated as missing values, which account for about 4×10^{-6} of the total daily SAT records.

c. *Definition of extreme temperature indices*

We use a set of total 16 temperature indices, including 15 extreme temperature indices (ETIs), among which 13 are adopted, with no modification, from the definitions by the Expert Team on Climate Change Detection and Indices (ETCCDI), and the remaining 2 are monthly-mean Tmax and Tmin. Monthly-mean temperature is also applied. Definitions and units of the temperature indices are shown in Table 1. They can be broadly divided into three categories: absolute threshold indices, relative threshold indices, and the mean and extreme value indices.

The mean and extreme value indices are simply the mean and extreme values of Tmax and Tmin during a certain period, including mean Tmax and Tmin, the highest Tmax (TXX) and Tmin (TNX), the lowest Tmax

(TXN) and Tmin (TNN), DTR, and monthly- and annual-mean SAT or Tavg (TM).

The absolute threshold indices are those directly determined based on original daily data and fixed thresholds, including frost days (FD0), summer days (SU25), ice days (ID0), and tropical nights (TR20). For these indices, there will be some stations without records of extremes for some or even all years of the time period analyzed. In this case, we determine that if a station has no record of extremes for ⅓ yr of the 48-yr period, the linear trend of the index series for the station is regarded as being insignificant, and the station is no longer included in the statistics of the index time series.

The relative threshold indices are defined based on relative (floating) thresholds, including cool days (nights) and warm days (nights). We take the 90th (10th) percentile values of daily Tmax (Tmin) data in a certain station from 1971 to 2000 as the upper (lower) thresholds. If the daily Tmax (Tmin) is greater (less) than the upper (lower) threshold, the day (night) is considered as a warm (cool) day (night) event.

d. Analysis methods

We apply a method of comparing average ETI series between the RCBMS and the reference stations on a basis of longitude by latitude grids. The size of grids is 5° × 5°. Only those grids with both the RCBMS and the reference stations are analyzed, and there are thus a total of 42 grids in the study region (Fig. 1). The eight grids that own only the RCBMS but no reference stations are all located along the national boundaries or coastal lines and are of incomplete grids. In addition, there are three grids in which the RCBMS and the reference stations are at the same sites in the northwestern Qinghai–Tibetan Plateau resulting from the lack of observations, and they are not included in the analysis either. Therefore, each of the grids analyzed owns at least one station of the RCBMS and one reference station, with those of the eastern parts of the study region generally having more observational records.

The following terms are used in this paper, referring to Chu and Ren (2005), Ren et al. (2008), and L. Zhang et al. (2011).

The urbanization effect (ΔT_{u-r}) refers to the impact of urbanization on SAT trends. It is here defined as the linear trend of the ETI of a station or a group of stations, caused by the strengthening UHI effect and other local anthropogenic factors near the stations, and is expressed as

$$\Delta T_{u-r} = T_u - T_r, \tag{1}$$

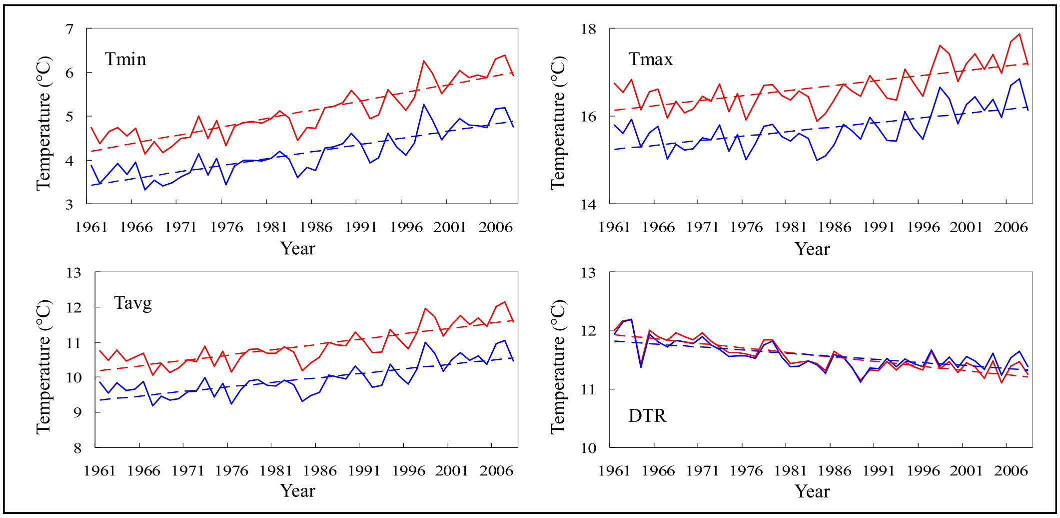
where T_u is the linear trend of any ETI of an urban/town station or stations of the RCBMS within a grid, and T_r is the linear trend of any ETI of reference stations within the grid. A value of $\Delta T_{u-r} > 0$ indicates that the ETI relatively increases at the urban/town station or stations of the RCBMS because of the urbanization effect, mainly to the enhanced UHI effect; $\Delta T_{u-r} < 0$ implies that the ETI at the urban/town station or stations of the RCBMS relatively decreases because of the urbanization effect, including the local anthropogenic factors other than the UHI effect.

Urbanization contribution (C_u) is defined as the proportion that the statistically significant urbanization effect accounts for the overall ETI trend at an urban/town station or stations of the RCBMS (Chu and Ren 2005; Ren et al. 2008). It can be expressed as

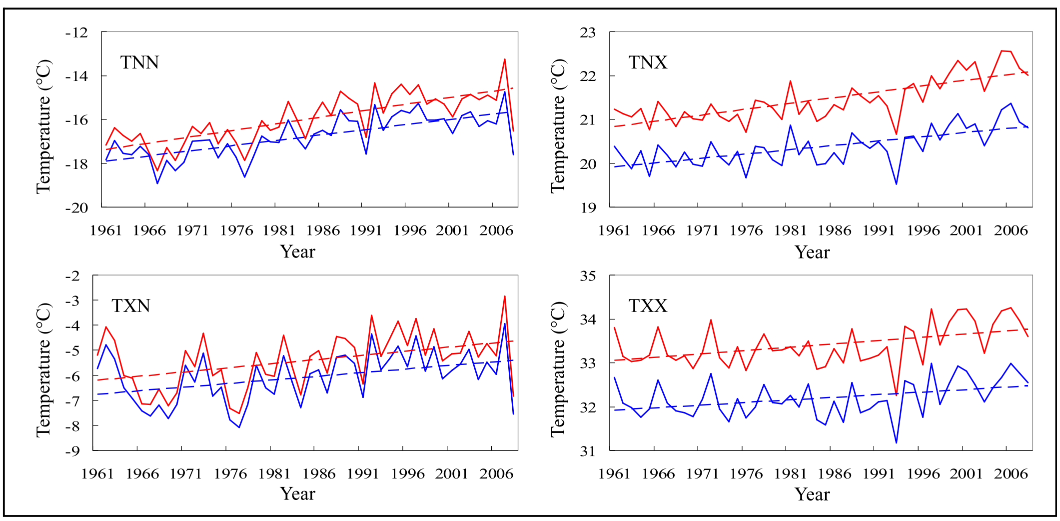
$$C_u = \left|\frac{\Delta T_{u-r}}{T_u}\right| \times 100\%. \tag{2}$$

Generally, $\Delta T_{u-r}/T_u$ is a positive value less than 1; the absolute value is taken because in a few circumstances it assumes negative value resulting from the effects of local factors other than increasing UHI intensity. If C_u = 100%, then it shows that the ETI trend of the urban station is entirely caused by urbanization; if C_u is more than 100%, it implies that the extra trend might have been caused by other local factors not yet identified or the errors of data, but it is regarded as 100% in this study. As the definition implies, urbanization contribution is not calculated if the urbanization effect is not statistically significant.

The grid-averaged annual and seasonal ETIs series of the RCBMS and reference stations for each of the 42 grids are first calculated, respectively, for the 48 yr. With the period 1971–2000 taken as reference period, RClimDex software (Zhang and Yang 2004) is used to calculate the time series of the ETIs for each of the stations. The grid-averaged ETIs series are then obtained by simply averaging all values within the grids for each of the 48 yr. The respective linear trends of the ETIs for the RCBMS and reference stations are calculated using the least squares method. This requires the calculation of the linear regression coefficients between any grid-averaged ETIs and ordinal numbers of time (e.g., i = 1, 2, 3, . . . , 48 for 1961–2008). Once the grid-averaged ETIs series and their trends are obtained, ΔT_{u-r} and the C_u then can be calculated for each of the grids by applying Eqs. (1) and (2). (The annual values in Figs. 5, 7, 9, and 11 have been obtained this way.) The country-averaged ETIs series of the RCBMS and reference stations are obtained by area-weighted averaging of the values of all the grids, with the weights assigned as the cosine midlatitude values of the grids (Figs. 2, 3) (Jones and Hulme 1996). Linear trends of the country-averaged



(a)



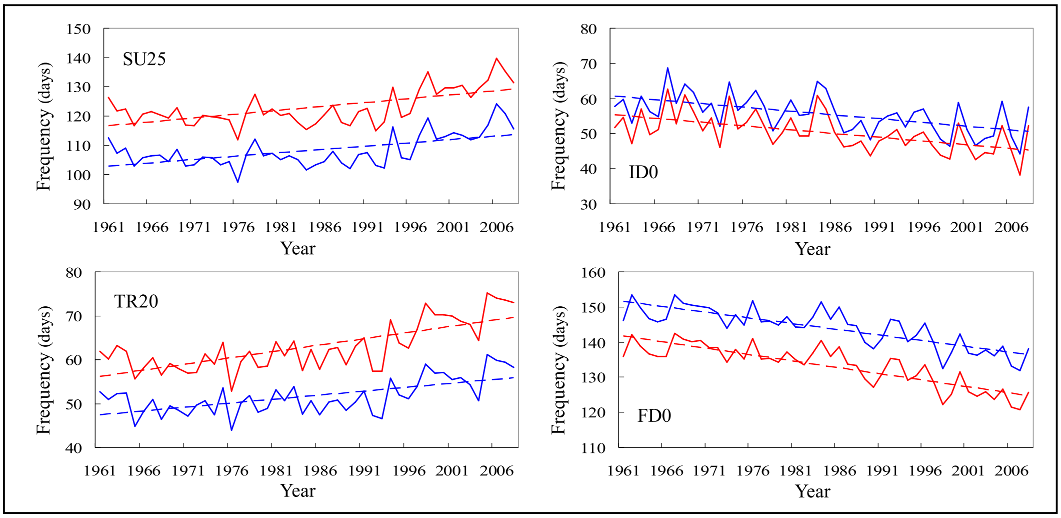
(b)

FIG. 2. Changes in mean and extreme value indices for the RCBMS (red) and the reference/rural stations (blue) in mainland China over 1961–2008 for (a) Tmin, Tmax, Tavg, and DTR; and (b) TNN, TNX, TXN, and TXX. Straight dashed lines denote linear trends.

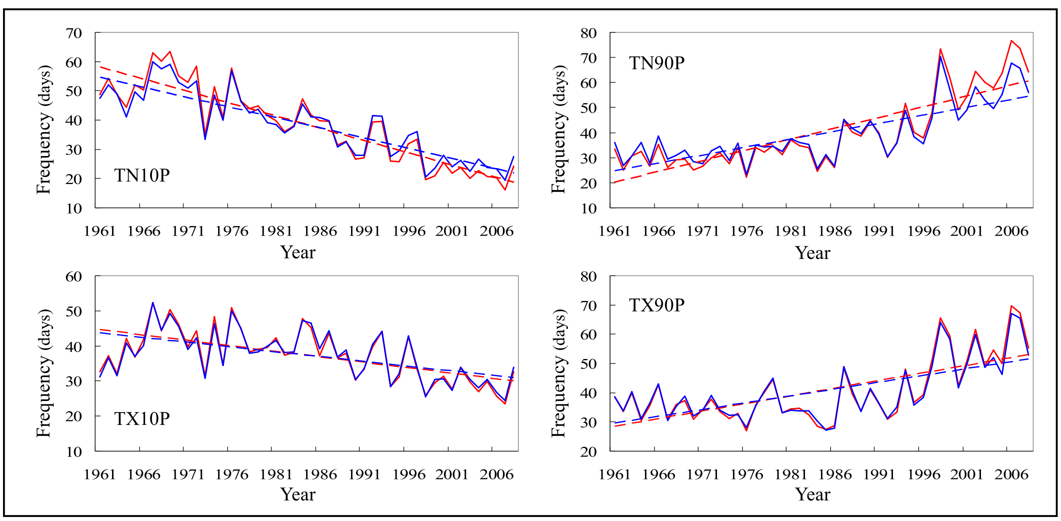
ETIs series are then calculated for the RCBMS and the reference stations (Table 2), and the country-averaged ΔT_{u-r} and C_u of the RCBMS are obtained by applying Eqs. (1) and (2). The annual and seasonal values in Tables 3 and 4 have thus been obtained.

To visualize the temporal change in the country-averaged ΔT_{u-r}, we also construct on the basis of the grids the difference value series of the grid-averaged ETIs between the RCBMS and reference stations and then obtain the time series of the country-averaged difference values of the ETIs between the RCBMS and the reference stations applying an area-weighted averaging method. The annual country-averaged difference value series visually exhibit the temporal variation in country-averaged annual ΔT_{u-r} for the ETIs of the RCBMS. (Figures 4, 6, 8, and 10 have been drawn based on the values of the annual ΔT_{u-r}.)

Kendall's tau nonparametric test method is applied for examining the statistical significance of the linear trends and ΔT_{u-r} (Kendall and Gibbons 1990; von Storch and Zwiers 2003). Meteorological seasons are adopted for the analysis of seasonality, and they are respectively spring (March–May), summer (June–August), autumn (September–November), and winter (December–February). Annual-mean (total) values (counts) are those from January to December.



(a)



(b)

FIG. 3. As in Fig. 2, but for absolute and relative threshold indices: (a) SU25, ID0, TR20, and FD0; and (b) TN10p, TN90p, TX10p, and TX90p.

3. ETIs trends of the RCBMS

Table 2 shows the annual- and seasonal-mean linear trends in the ETIs series for the RCBMS in mainland China over the time period 1961–2008. Statistically significant changes can be found for all of the annual-mean ETIs series and for seasonal-mean trends of the ETIs series except for the increases in spring TXN and summer TXX. Larger and more significant trends generally occur in the ETIs series relative to the daily minimum temperature. With regard to the annual-mean trends, the largest changes are seen for the increase in the lowest Tmin and warm nights, reaching 0.596°C $(10\,\mathrm{yr})^{-1}$ and 8.584 days $(10\,\mathrm{yr})^{-1}$, respectively, and the decrease in cold nights at a rate of -8.409 days $(10\,\mathrm{yr})^{-1}$, all related to the minimum temperature. The largest changes of seasonal-mean ETIs occur in the decrease of cold nights in winter and the increase of warm nights in summer, reaching -11.108 and 10.184 days $(10\,\mathrm{yr})^{-1}$, respectively.

Figures 2 and 3 show changes in the ETIs of the RCBMS and reference stations in mainland China over the period 1961–2008. Extremely good correlations between the two datasets can be seen, especially for interannual variability of the ETIs. The linear trends of the ETIs series of the RCBMS exhibit the consistent

TABLE 2. Trends in extreme temperature indices series for the national RCBMS in mainland China over 1961–2008. Units are degrees Celsius per decade [°C $(10\,\mathrm{yr})^{-1}$] for Tmin, Tmax, Tavg, DTR, TNN, TNX, TXN, and TXX, and days per decade for TN10p, TN90p, TX10p and TX90p. An asterisk denotes that the trends are statistically significant at the 0.05 confidence level.

	Tmin	Tmax	Tavg	DTR	TNN	TNX	TXN	TXX
Annual	0.381*	0.228*	0.305*	−0.154*	0.596*	0.264*	0.331*	0.150*
Spring	0.364*	0.200*	0.282*	−0.167*	0.444*	0.253*	0.180	0.131*
Summer	0.279*	0.138*	0.209*	−0.144*	0.493*	0.218*	0.151*	0.105
Autumn	0.339*	0.264*	0.301*	−0.074*	0.544*	0.338*	0.389*	0.327*
Winter	0.542*	0.311*	0.426*	−0.230*	0.565*	0.435*	0.321*	0.330*
	SU25	ID0	TR20	FD0	TN10p	TN90p	TX10p	TX90p
Annual	2.622*	−2.140*	2.884*	−3.579*	−8.409*	8.584*	−3.113*	5.230*
Spring					−7.532*	8.599*	−1.892*	4.830*
Summer					−7.495*	10.184*	−1.496*	4.906*
Autumn					−7.854*	7.871*	−4.305*	5.941*
Winter					−11.108*	7.870*	−5.074*	5.353*

patterns of changes with those shown in Table 2, but they usually witness larger trends than those of the reference stations, in particular for the ETIs formulated from minimum temperature, such as Tmin, DTR, TNN, TN10p), and TN90p. The systematically higher annual values and mean values of the RCBMS than those of the reference stations for the absolute threshold and extreme value indices might have been induced mainly by different average altitudes of the two observational networks and might have also been related to the urbanization effects to some extent.

Trends of the temperature indices of the RCBMS shown in Table 2, Figs. 2 and 3 are almost all consistent with the recent analyses (Zhou and Ren 2011; Ren et al. 2011; You et al. 2013) and well comparable with earlier studies conducted for mainland China, including those by Zhai et al. (1999), Yan et al. (2002), Zhai and Pan (2003), Qian and Lin (2004), and Gong and Han (2004), despite the fact that the stations, the data processing procedures, and the time periods applied in the analyses bear some differences from the present study. Our analysis results are also broadly consistent with those reported for larger spatial-scale studies outside mainland China (e.g., Easterling et al. 2000; Alexander et al. 2006; Solomon et al. 2007; Choi et al. 2009). The next issue is whether or not, or to what extent, the significant changes for the various ETIs in mainland China have been caused by the locally anthropogenic interferences or urbanization.

4. Urbanization effects and contributions

a. Extreme value indices

Table 3 gives annual- and seasonal-mean urbanization effects and contributions of the RCBMS for Tmin, Tmax, Tavg, and DTR over the time period 1961–2008. Annual- and seasonal-mean urbanization effects for mainland China as a whole are all statistically significant at the 0.05 confidence level for Tmin, Tmax, and Tavg, with the annual-mean urbanization effects for the three indices reaching 0.070°, 0.023°, and 0.047°C $(10\,\mathrm{yr})^{-1}$, respectively, and the urbanization contributions reaching 18.4%, 10.1%, and 15.4%, respectively. Larger urbanization effects are found for Tmin for winter and spring,

TABLE 3. Urbanization effect (UE) and urbanization contribution (UC) of the RCBMS of mainland China for Tmin, Tmax, Tavg, DTR, TNN, TNX, TXN, and TXX over the time period 1961–2008. An asterisk denotes that the trends are statistically significant at the 0.05 confidence level.

		Tmin	Tmax	Tavg	DTR	TNN	TNX	TXN	TXX
Annual	UE [°C $(10\,\mathrm{yr})^{-1}$]	0.070*	0.023*	0.047*	−0.049*	0.118*	0.069*	0.045*	0.034*
	UC (%)	18.4	10.1	15.4	31.8	19.8	26.1	13.6	22.7
Spring	UE [°C $(10\,\mathrm{yr})^{-1}$]	0.072*	0.015*	0.044*	−0.060*	0.112*	0.052*	0.016	0.012
	UC (%)	19.8	7.5	15.6	35.9	25.2	20.6		
Summer	UE [°C $(10\,\mathrm{yr})^{-1}$]	0.057*	0.028*	0.043*	−0.031*	0.100*	0.057*	0.019	0.016
	UC (%)	20.4	20.3	20.6	21.5	20.3	26.1		
Autumn	UE [°C $(10\,\mathrm{yr})^{-1}$]	0.063*	0.022*	0.043*	−0.043*	0.082*	0.029	0.031	0.005
	UC (%)	18.6	8.3	14.3	58.1	15.1			
Winter	UE [°C $(10\,\mathrm{yr})^{-1}$]	0.083*	0.024*	0.054*	−0.061*	0.102*	0.036*	0.032	0.004
	UC (%)	15.3	7.7	12.7	26.5	18.1	8.3		

TABLE 4. As in Table 3, but for SU25, ID0, TR20, FD0, TN10p, TN90p, TX10p, and TX90p.

		SU25	ID0	TR20	FD0	TN10p	TN90p	TX10p	TX90p
Annual	UE [days $(10\,yr)^{-1}$]	0.335*	−0.013	1.090*	−0.360*	−1.485*	2.264*	−0.390*	0.561*
	UC (%)	12.8		37.8	10.1	17.6	26.4	12.5	10.7
Spring	UE [days $(10\,yr)^{-1}$]					−1.526*	2.292*	−0.037	0.263
	UC (%)					20.3	26.7		
Summer	UE [days $(10\,yr)^{-1}$]					−1.310*	3.435*	−0.580*	0.956*
	UC (%)					17.5	33.7	38.8	19.5
Autumn	UE [days $(10\,yr)^{-1}$]					−1.332*	2.029*	−0.332*	0.730*
	UC (%)					17.0	25.8	7.7	12.3
Winter	UE [days $(10\,yr)^{-1}$]					−1.865*	1.343*	−0.588*	0.307*
	UC (%)					16.8	17.1	11.6	5.7

reaching 0.083° and 0.072°C $(10\,yr)^{-1}$, respectively, and the smallest urbanization effect and contribution, 0.015°C $(10\,yr)^{-1}$ and 7.5%, respectively, are seen for Tmax for spring, which might have been related to the higher average wind speeds and the generally weakened urban heat island intensity of the afternoons in the season (Zhang and Lin 1992; Gao et al. 2013; Yang et al. 2013). Overall, the annual- and seasonal-mean urbanization contributions for Tmin, Tmax, and Tavg for the 48 yr range from 7.5% to 20.6%, with the largest seasonal-mean contributions occurring in summertime. Table 3 also shows that annual- and seasonal-mean urbanization effects for DTR in mainland China as a whole are all statistically significant at the 0.05 confidence level. The largest decline of seasonal-mean DTR because of urbanization are found in winter and spring, reaching −0.061° and −0.060°C $(10\,yr)^{-1}$, respectively, but the largest urbanization contributions appear in autumn and spring, reaching 58.1% and 35.9%, respectively, for the study region as a whole.

Figure 4 shows the temporal variation in annual-mean urbanization effects as calculated based on the differences between the RCBMS and reference stations in mainland China as a whole for Tmin, Tmax, Tavg, and DTR over the time period 1961–2008. The annual differences have very similar interannual and long-term variations for Tmin and Tavg, with the significant increase obviously occurring after 1976, and the lowest values are almost all found in the time period 1966–76 when an unprecedented deurbanization process occurred across mainland China during the Cultural Revolution (1966–76). Although a significant increase in the annual urbanization effects is also seen for Tmax, they experience a larger interannual and decadal variability. A highly significant decline occurs in the DTR difference series, with the largest values found once again during 1966–76 and the smallest ones in the last 6 yr. It is also notable that, except for the DTR, average values of the annual differences between the RCBMS and reference stations for the first years of the indices

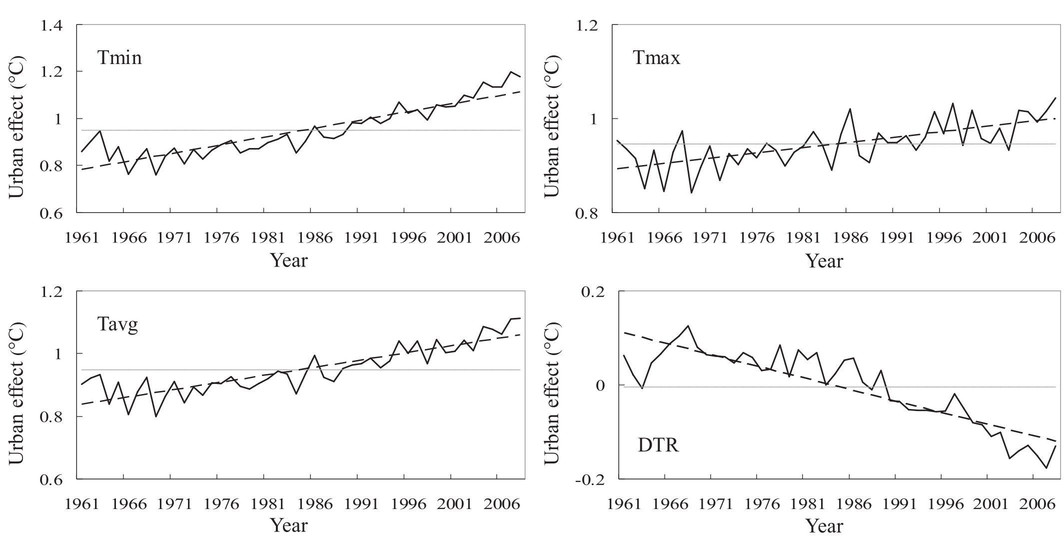


FIG. 4. Temporal variations in annual differences between the RCBMS and reference stations for Tmin, Tmax, Tavg, and DTR in mainland China over the time period 1961–2008.

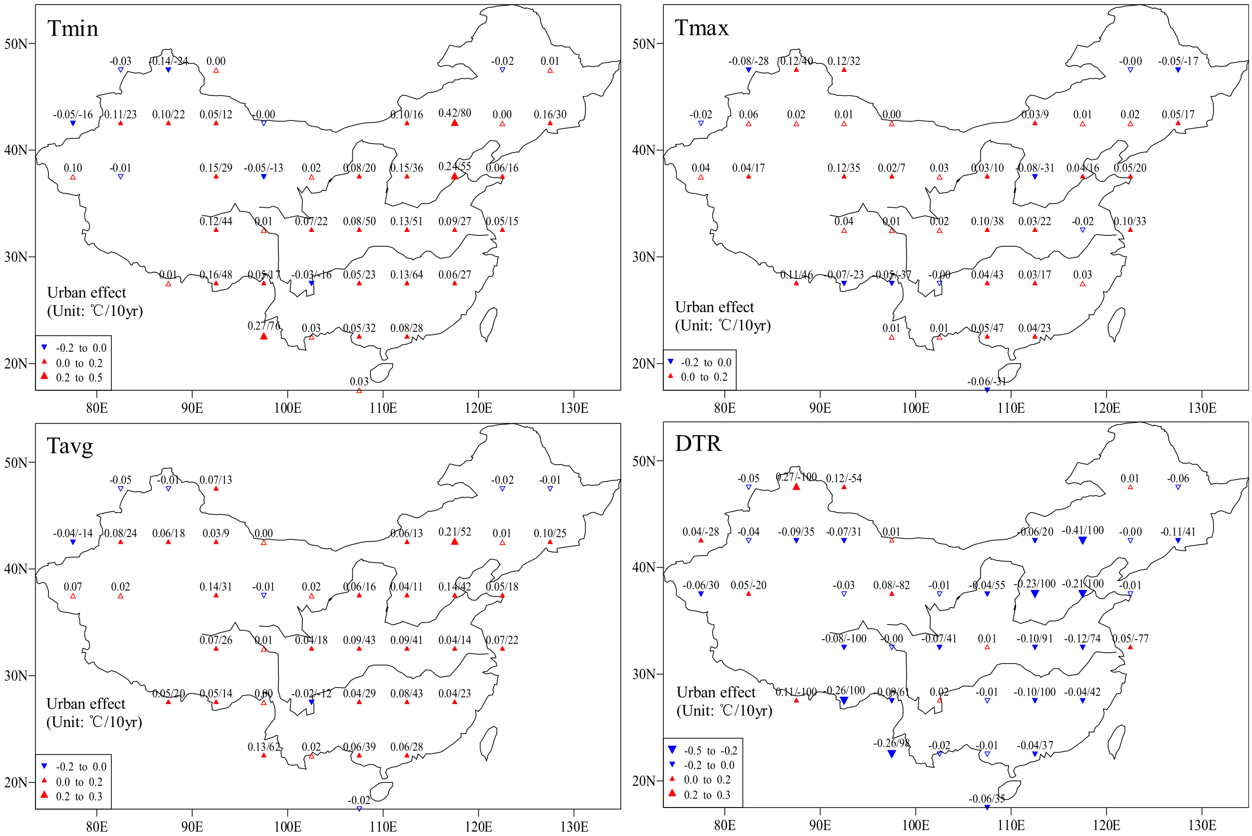


FIG. 5. Spatial distributions of urbanization effects and contributions of annual-mean Tmin, Tmax, Tavg, and DTR in mainland China over the time period 1961–2008. The solid (hollow) triangle denotes that the urbanization effect is (is not) significant at the 0.05 confidence level. The value to the left is urbanization effect [°C $(10\,\mathrm{yr})^{-1}$] and to the right is urbanization contribution (%).

series are well above zero, with those of Tmin and Tavg close to 0.80°–0.90°C, implying that either the RCBMS are generally lower in heights than the reference stations, or the urbanization effects for the RCBMS actually began well before 1961.

In view of the spatial distributions of urbanization effects and contributions (Fig. 5), the largest and more significant urbanization effects for Tmin occur in north China, generally ranging from 0.10° to 0.30°C $(10\,\mathrm{yr})^{-1}$, with the urbanization contributions generally ranging from 20% to 60%. Most of the grids registers the significant positive urbanization effects for annual-mean Tmin in mainland China, but almost half of the grids in arid northwestern China witness negative urbanization effects with half of them being significant at the 0.05 confidence level. By contrast, there are fewer grids where significant positive urbanization effects are spotted for annual-mean Tmax, despite the fact that most of the grids similarly have positive values of urbanization effects and the significant negative values in a few grids are more evenly distributed across the country. Annual-mean SAT sees a similar spatial pattern, and the largest and more significant urbanization effects, mostly ranging from 0.06° to 0.14°C $(10\,\mathrm{yr})^{-1}$, are found in the grids of north China and the lower Yangtze basin. There is a relatively coherent distribution of the DTR urbanization effects across mainland China, and most of the grids experience a decrease because of urbanization, with more than 80% of them registering a significant urbanization effect. The largest urban-induced decrease in the annual-mean DTR are seen in north China and the southeastern Tibetan Plateau, and a 100% urbanization contribution appears in five grids of the two regions, indicating a thorough urbanization effect on the decrease of the annual-mean DTR during the past 48 yr in these areas.

Table 3 also shows annual- and seasonal-mean urbanization effects and contributions of the RCBMS for TNN, TNX, TXN, and TXX over the time period 1961–2008, and Fig. 6 shows the temporal changes in annual-mean urbanization effects as calculated based on the differences between the RCBMS and reference stations in mainland China as a whole for the four indices for the same time period. It is evident that all of the annual

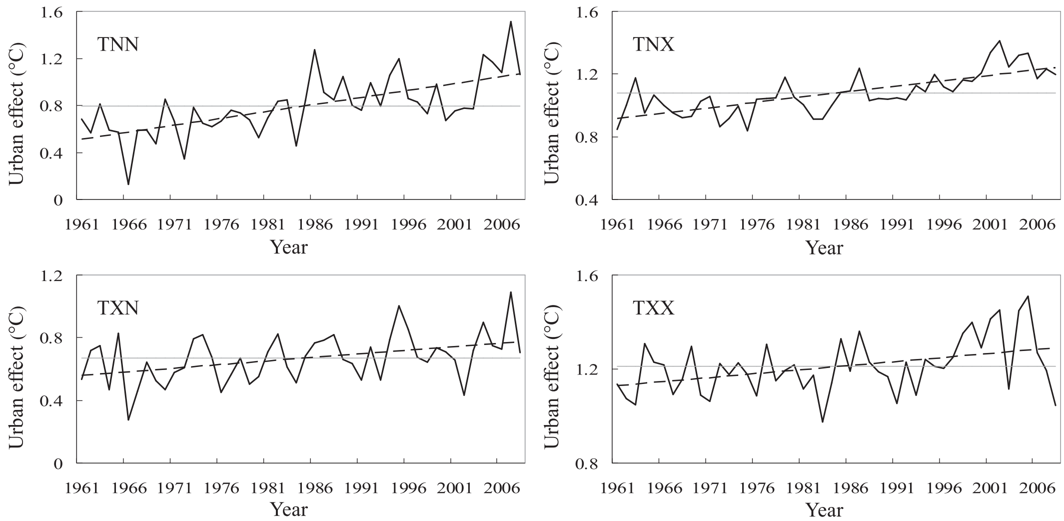


FIG. 6. As in Fig. 4, but for TNN, TNX, TXN, and TXX.

extreme values of Tmin and Tmax experience upward trends, and more significant increases can be seen for TNN and TNX, despite the fact that a larger interannual variability appears in the four indices compared to Tmin, Tmax, Tavg, and DTR. Annual- and seasonal-mean urbanization effects for TNN are all statistically significant at the 0.05 confidence level, with the annual value reaching 0.118°C $(10\,\mathrm{yr})^{-1}$ and the annual-mean urbanization contribution reaching 19.8%. Although the seasonal-mean urbanization effects for TXN and TXX are all positive for the four seasons, none of them are statistically significant at the 0.05 confidence level (Table 3).

Figure 7 shows spatial distributions of annual-mean urbanization effects and contributions for TNN, TNX, TXN, and TXX over the time period 1961–2008. Most of the grids witness increases, and the largest and more significant increases, generally above 0.150°C $(10\,\mathrm{yr})^{-1}$ for urbanization effect, are seen for TNN in north China and the northern Qinghai–Tibet Plateau. The positive urbanization effects are also seen for TNX in north China and southeastern China to a lesser extent. The annual-mean urbanization effects for TXN and TXX, however, are usually not so significant with the exceptions of a few of grids in the coastal regions and southeast China. Overall, a more heterogeneous distribution of urbanization effects can be seen for the four indices especially for TXN and TXX, as compared to the spatial uniformity for Tmin, Tmax, Tavg, and DTR.

b. *Absolute threshold indices*

Table 4 and Fig. 8 exhibit urbanization effects of the RCBMS for SU25, ID0, TR20, and FD0 for the time period 1961–2008. Urbanization leads to an increase in annual total days of SU25 and TR20, but to a decrease in annual total days of ID0 and FD0, and the annual effects are statistically significant except for ID0, with the upward trend reaching 1.090 days $(10\,\mathrm{yr})^{-1}$ for the tropical night frequency and an urbanization contribution as high as 37.8%. Urbanization effects are −0.360 and 0.335 days $(10\,\mathrm{yr})^{-1}$, respectively, for frost days and summer days, and the urbanization contributions are 10.1% and 12.8%, respectively, for the two indices. An insignificant urbanization effect has been detected for ice days over mainland China as a whole, consistent with the insignificant change in annual-mean Tmax. Figure 8 also shows that the linear trends of TR20 and FD0 are larger and more significant, especially after 1976 when the 10-yr Cultural Revolution ended and the economic growth and urbanization of mainland China began to accelerate.

Figure 9 shows spatial distributions of urbanization effects and contributions of annual-mean SU25, ID0, TR20, and FD0 over the time period 1961–2008. With the exception of ID0, the indices exhibit coherent urbanization effects in the regions where the trends can be analyzed. SU25 or summer days are generally characterized by positive urbanization effects, and the most remarkable urbanization-induced increases in summer days, with trends ranging from 0.60 to 1.50 days $(10\,\mathrm{yr})^{-1}$ and contributions ranging from 20% to 50%, occur in northern and central China. More spatially coherent distributions of urbanization effects are seen for TR20 and FD0, with the TR20 urbanization effects mostly exhibiting significantly positive trends of 1.00–3.00 days $(10\,\mathrm{yr})^{-1}$ and urbanization contributions ranging from 30% to 100% in north China and southeastern China, and the FD0 urbanization effects showing significantly negative

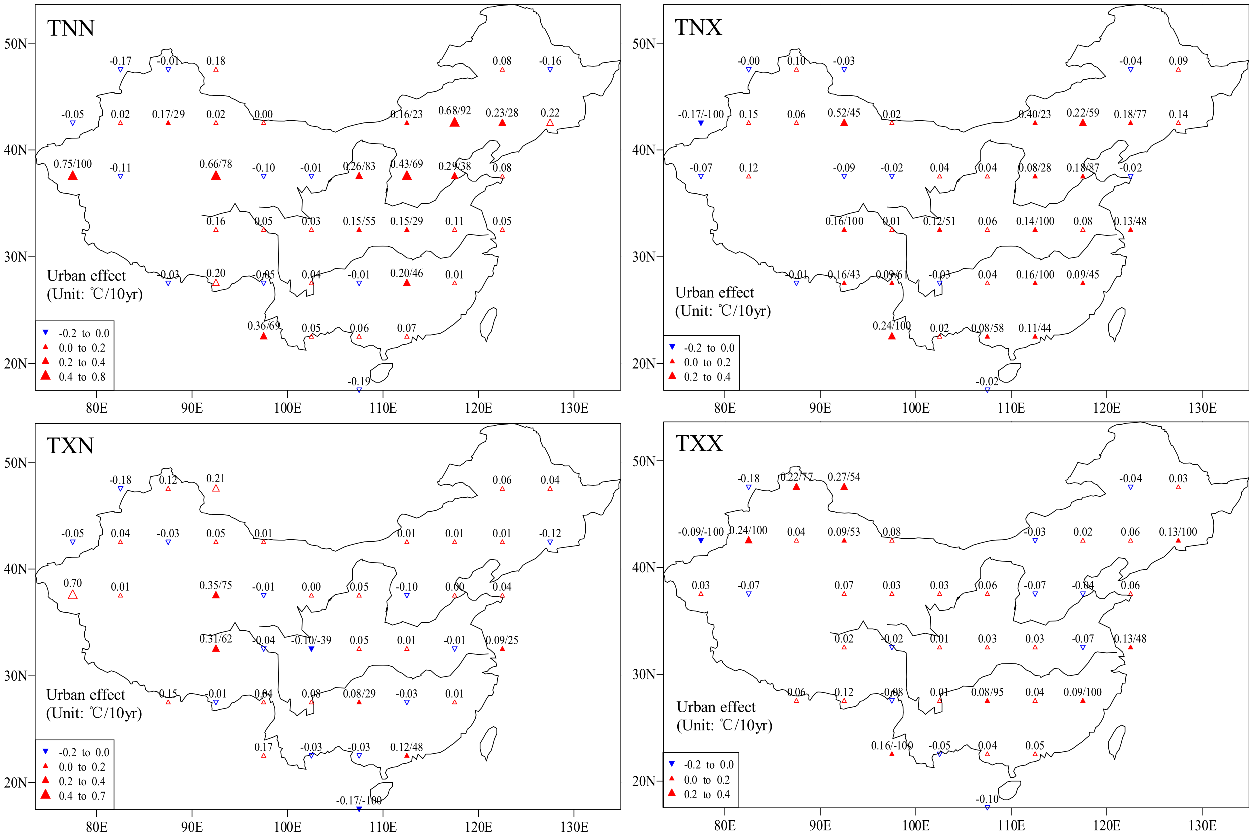


FIG. 7. As in Fig. 5, but for TNN, TNX, TXN, and TXX.

trends from -1.00 to -3.00 days $(10\,\mathrm{yr})^{-1}$ and urbanization contributions ranging from 20% to 80% in north China. The coherent urbanization effects are not found for ID0 or ice days despite the fact that more negative values can be seen in northwestern China, which is well consistent with the insignificant trend detected in the country-averaged annual ID0 difference series between the RCBMS and reference stations.

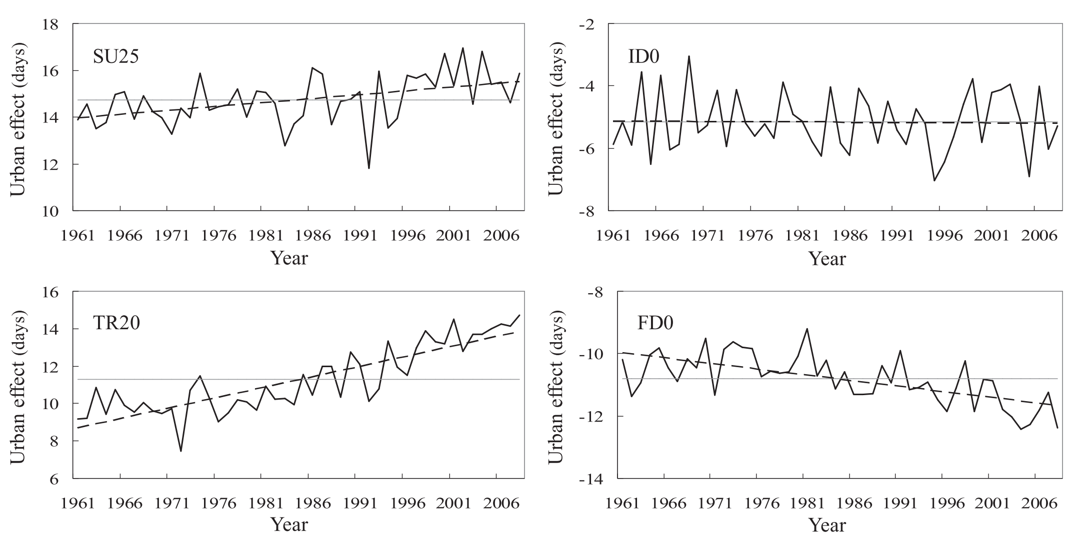


FIG. 8. As in Fig. 4, but for SU25, ID0, TR20, and FD0.

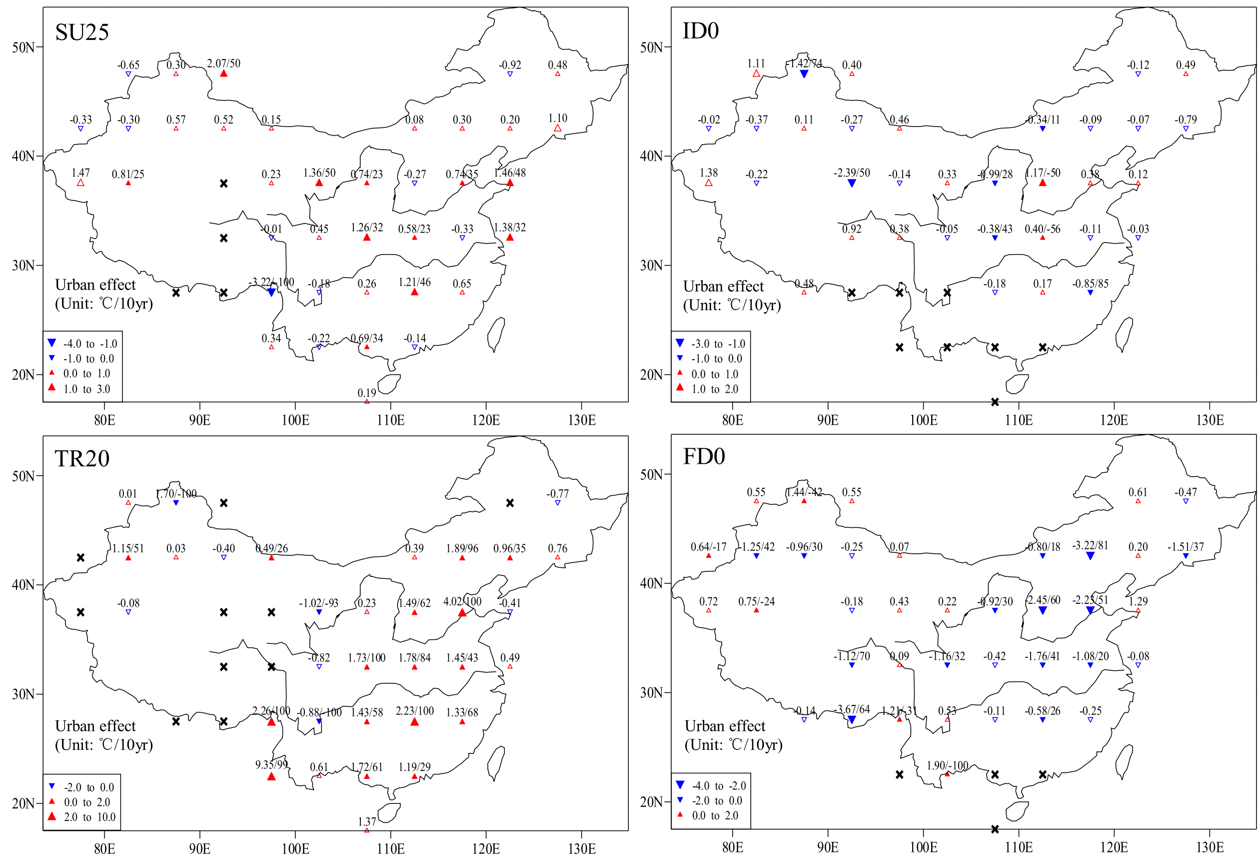


FIG. 9. As in Fig. 5, but for SU25, ID0, TR20, and FD0. Black diagonal crosses indicate the grids where urbanization effects cannot be analyzed because of lacking or incomplete time series of the index.

c. *Relative threshold indices*

Table 4 also gives urbanization effects and contributions of the RCBMS for TN10p, TN90p, TX10p, and TX90p for the time period 1961–2008, and Fig. 10 shows the temporal change in annual-mean urbanization effects as calculated based on the differences between the RCBMS and reference stations in mainland China for TN10p, TN90p, TX10p, and TX90p for the same time period. The annual-mean urbanization effects are all statistically significant for the four indices over mainland China. Urbanization has led to a highly significant decline of annual-mean cold night frequency at a rate of -1.485 days $(10\,\text{yr})^{-1}$, which accounts for 17.6% of the overall decrease as observed in the RCBMS, and a tremendous increase of annual-mean warm night frequency at a rate of 2.264 days $(10\,\text{yr})^{-1}$, which accounts for 26.4% of the overall increase as observed in the RCBMS. The urbanization-induced decline of cold nights mainly occurred after 1976, and the urbanization-induced increase of warm nights dominantly appeared after the beginning of the 1990s. Although the urbanization effects are also statistically significant for cold days and warm days, they are relatively smaller and less significant as compared to cold nights and warm nights. It is interesting to note that the decline of the cold indices (TN10p and TX10p) generally began about 20 yr earlier than the increase of the warm indices (TN90p and TX90p), probably related to the earlier popularization of heating in winter than the widespread application of air conditioning in summer in cities of mainland China.

Seasonal-mean urbanization effects are statistically significant for all of the relative indices and seasons except for cold days and warm days of spring. The largest seasonal-mean trend because of urbanization is seen for warm nights of summer, reaching 3.435 days $(10\,\text{yr})^{-1}$ with an urbanization contribution of 33.7%. The positive urbanization effects are also larger for warm nights of spring and autumn. Reasons for the insignificant urbanization effects for cold days and warm days of spring need to be further examined, but they might have been related to the weakest afternoon UHI intensity resulting from the larger number of days with strong wind during

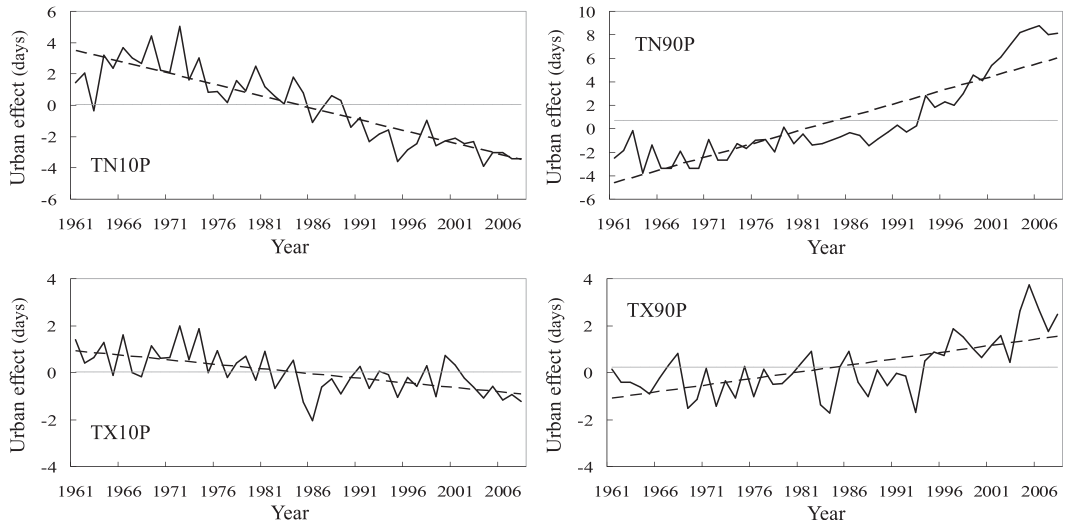


FIG. 10. As in Fig. 4, but for TN10p, TN90p, TX10p, and TX90p.

the season of a year, especially in northern China (Gao et al. 2013; Yang et al. 2013).

Figure 11 shows spatial distributions of urbanization effects and contributions of annual-mean TN10p, TN90p, TX10p, and TX90p in mainland China over the time period 1961–2008. Both cold nights and warm nights exhibit highly coherent urban-induced trends across mainland China. The negative (positive) TN10p (TN90p) urbanization effects are statistically significant for most grids, indicating the tremendous decrease (increase) in cold nights (warm nights) because of the rapid urbanization near the National Stations during the 48-yr period. A few exceptions mainly occur in the northwestern and northeastern parts of the country, consistent with the spatial patterns of the urbanization effects of annual-mean Tmin (Fig. 5). The largest urbanization effects for both TN10p and TN90p, usually ranging from 1.50 to 5.00 days $(10\,\mathrm{yr})^{-1}$ for absolute values with urbanization contributions mostly ranging from 20% to 60%, are seen in north China, the mid-to-lower Yangtze basin, and the eastern part of the Qinghai–Tibet Plateau. Although the TN10p sees larger urbanization effects in northern regions, the TN90p experiences somewhat larger urban-induced warming in southern grids.

Similar to the urbanization effects of the annual-mean Tmax, and obviously different from those of annual-mean Tmin, the annual-mean TX10p and TX90p urbanization effects exhibit generally less spatial coherence across the country than the annual-mean TN10p and TN90p (Fig. 11). Significant decrease (increase) of cold days (warm days) because of urbanization usually appears in northern, central, and southern China, with the absolute values mostly reaching 0.50–2.00 days $(10\,\mathrm{yr})^{-1}$ and the urbanization contributions reaching 10%–50%. The insignificant urbanization effects are seen mainly in western regions and northern northeast China.

5. Discussion

Statistically significant changes in extreme temperature indices during the past half a century have been reported for all continents except the Antarctic region (e.g., Karl et al. 1993; Easterling et al. 2000; Manton et al. 2001; Frich et al. 2002; Alexander et al. 2006; Solomon et al. 2007; Qian et al. 2007; Ren et al. 2010a, 2011; X. B. Zhang et al. 2011). These changes are closely related to the significant increase in the global and regional average annual-mean SAT, as both the extreme temperature indices and the mean temperature are dependent on daily maximum and minimum temperature records. The previous studies examined urbanization effects on annual- and seasonal-mean SAT trends as observed in the commonly used datasets or in the records from urban stations in some regions of the global continents and found significant urban warming in the regional average temperature series (e.g., Karl et al. 1988; Hansen et al. 2001; Zhou et al. 2004; Ren et al. 2005, 2008, 2012; Fujibe 2009; Zhang et al. 2010; Fall et al. 2010; Yang et al. 2011). It is therefore natural to assume that urbanization also exerts an nonnegligible effect on the trends of the extreme temperature indices.

Chen et al. (2005) analyzed the urbanization effects on regional trends of annual- and seasonal-mean Tmin and Tmax in Hubei Province, China, and found generally larger urbanization effects in the Tmin series than in the Tmax series. Hua et al. (2008) reported large urbanization effect in minimum temperature series of city stations of the RCBMS in winter over mainland China,

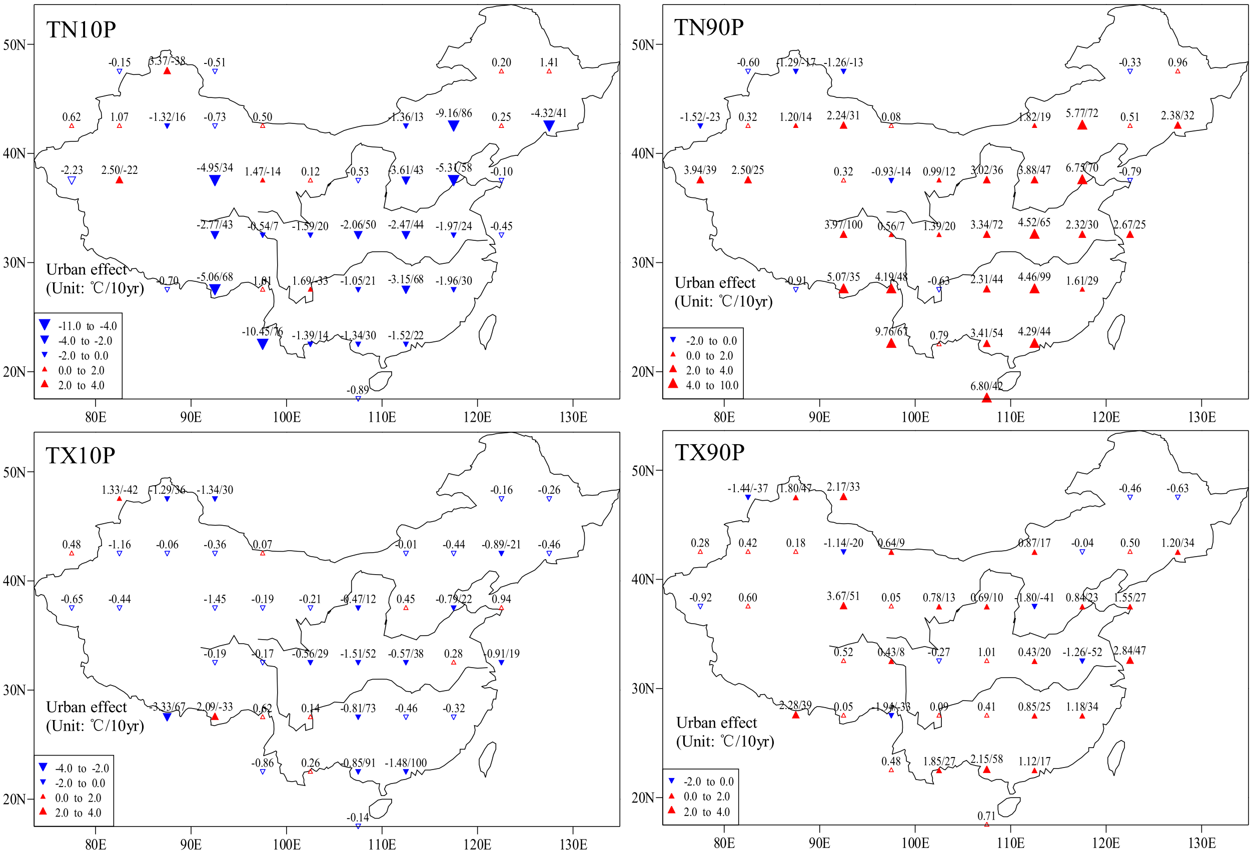


FIG. 11. As in Fig. 5, but for TN10p, TN90p, TX10p, and TX90p.

despite the evident regional differences of the urban warming. Zhou and Ren (2009) analyzed annual- and seasonal-mean urbanization effects on linear trends of Tmax, Tmin, and DTR for the RCBMS in north China and found highly significant urbanization effects in the regional average annual- and seasonal-mean Tmin and DTR series, with the urbanization contributions reaching 53% for annual-mean Tmin and 100% for annual-mean DTR. Zhou and Ren (2011) estimated urbanization effects on trends of different extreme temperature indices for the RCBMS in north China for the time period 1961–2008 and revealed highly significant urbanization effects in the ETIs series related to Tmin, with urbanization contributions reaching 44% and 48%, respectively, for frequencies of annual cold nights and annual warm nights and once again 100% for annual-mean DTR. Zhang et al. (2010) showed that north China is among the regions that experience the largest and most significant urbanization effects on annual-mean temperature trends of the past half a century over mainland China, though significant urban warming also occur in the other regions, except for northern Xinjiang of northwestern China.

Our analysis in this paper shows that urbanization effects in the country-averaged annual- and seasonal-mean Tmin and the Tmin-based ETIs series are also highly significant during the past half a century over mainland China, but magnitudes of the urbanization effects and the contributions to overall changes in the Tmin-based ETIs series are generally smaller than those reported for north China (Zhou and Ren 2011), probably due to the offset effect from the less developed regions in western China and northern northeast China. The largest urbanization effects and contributions of annual-mean DTR are found in north China and the southeastern Tibetan Plateau with five grids witnessing a thorough urbanization contribution to the decrease of the annual-mean DTR, which is well consistent with that reported for north China by Zhou and Ren (2009, 2011) and Zhang et al. (2010). The universally more significant urbanization effects in the Tmin-based ETIs series are also well consistent with those reported before for many regions and are understandable because the UHI intensity and its increase with time near the urban stations are dominantly larger during nighttime than during daytime in temperate and subtropical regions (Landsberg

1981; Oke 1987; Xie et al. 2006; Pielke et al. 2007; Yang et al. 2013). However, the results given in this paper are different from those reported for north China (Zhou and Ren 2011) in that a few of ETIs related to daily Tmax records, such as Tmax, TX10p, and TX90p, also witness significant urbanization effects in mainland China as a whole. This happens probably due to the larger and more significant urbanization effects on the Tmax-based ETIs trends in the southern parts of the country where the use of air conditioning during summer becomes more usual than before as economy grows and people's living standard rises, leading to a generally increasing UHI intensity near the observational sites.

In northwestern and northeastern China, there are a few grids where unexpectedly negative urbanization effects for some ETIs series, obviously for Tmin, Tavg, DTR, TR20, FD0, TN10p, and TN90p, are found. The ''paradox'' has been pointed out for northern northwest China by Zhang et al. (2010) in their study of mainland China. The urban stations of the RCBMS are mostly located in oasis areas in the northwestern arid region. The cool island effect in summer over the oases was reported (Su and Hu 1988). With urban growth, the oasis areas will expand, and SAT observations will be affected not only by increased UHI intensity or urbanization, but also by the oasis development and increasing cool island effect. It is thus possible that the stations near large cities, compared to those near rural and small towns, have undergone relative cooling trends with urbanization and oasis expansion (Zhang et al. 2010). Another reason for the distinct urbanization effects found in northwestern China might have been the relatively poor representativeness of the reference stations, as a few of them in the plains and basins had to be chosen from small cities or towns that might have undergone a rapider urbanization than big cities in the last decades.

Average values of the annual differences of the mean and extreme value indices and absolute threshold indices between the RCBMS and reference stations for the first years of the ETIs series are obviously deviated from zero, with those of Tmin, Tmax, Tavg, TNX, and TXX well above +0.8°C. This is related to the generally lower elevations of the RCBMS stations than the reference stations. Table 5 gives the average latitudes, longitudes, and heights of the RCBMS and reference stations. The average height is calculated from the area-weighted average grid values as done for SAT data. It is clear that little difference of average latitudes exists between the RCBMS and reference stations, but the average height of the RCBMS is about 327 m lower than that of the reference stations, leading to a generally higher SAT temperature in the RCBMS data. It is also possible that the urbanization effects on the extreme temperature indices had actually been felt by the very beginning years of the time period analyzed.

TABLE 5. Average latitudes, longitudes, and heights of the RCBMS and reference stations and the differences between the two networks. Note that mMSL refers to meters above sea level.

	Latitude (°N)	Longitude (°E)	Elevation (mMSL)
RCBMS	34.67	109.70	1258.56
Reference stations	34.00	105.69	1585.94
Difference	0.67	4.01	−327.38

Except for DTR and the four relative threshold indices, the smallest absolute values of the annual-mean urbanization effects or the annual differences of the ETIs between the RCBMS and reference stations in the country as a whole dominantly occur during the time period 1966–76. This is especially true for Tmin, Tavg, Tmax, TNN, TXN, TR20, and FD0. The 10-yr period is known as the Cultural Revolution when the country was in its unprecedented chaos and a measurable proportion of urban dwellers including the middle school graduates and university students were sent to the countryside for ''reeducation by farmers.'' The well-known deurbanization process across mainland China might have affected the UHI intensity near the urban stations, leading to the abnormally small urbanization effects as observed from the RCBMS. After the end of Cultural Revolution in 1976, the Chinese central government initiated the ''reform and opening up'' policy, the intellectual youth and other originally urban dwellers returned to cities, and economic growth and urbanization accelerated, leading to the increasing urbanization effects as detected from the country-averaged ETIs series of the RCBMS.

A major source of uncertainty is related to the dataset of the reference stations. Although great efforts had been made to select the reference stations (Ren et al. 2010b; Zhang et al. 2010), and a relatively high-quality dataset of 143 stations had been developed, there are still areas (grids) where no reference station is available. Furthermore, some reference stations in the northeast China plain, north China plain, and northwestern China had to be chosen from small cities and towns because of the lack of real rural stations with sufficient length of records. A consequence of the lowered standard for selecting reference stations is that the urbanization effects on the ETIs series of the RCBMS in this study must have been somehow underestimated. The underestimates for each of the indices series of the RBCMS need to be investigated in the future. In addition, even if the reference stations are truly located in rural areas, there might be more local effects of siting quality of observational grounds on surface air temperature trends (Fall et al. 2011; McNider et al. 2012), leading to extra nighttime warming for some of the stations. This issue, however, might be more serious for the RCBMS than for the reference stations, but the siting effect might have been included in the estimated urbanization bias of the ETIs series of the RCBMS in a large extent. Although improvement is needed to select more representatively reference stations, the 141 reference stations as used in this work are the best ones we are able to obtain at present.

Despite the uncertainties mentioned above, the urbanization effects in most of the ETIs series of the commonly applied climate dataset in mainland China are of significance, and they are not negligible, especially for those indices series related to daily minimum temperature records in the relatively developed areas of north China, central China, the mid-to-lower reaches of the Yangtze basin, and the southeastern coastal zone. It is also obvious from our analysis that urbanization effects cannot account for the overall changes in the ETIs in mainland China as a whole over the time period 1961–2008, and other factors or processes in addition to the local human influence would be important. These might include the increased concentration of greenhouse gases and aerosols in atmosphere, large-scale land use and land cover change, and the multidecadal natural variability of the climatic system mainly related to the ocean surface temperature variations.

6. Conclusions

Applying a homogeneity-adjusted daily temperature dataset of the Chinese national Reference Climate and Basic Meteorological Stations (RCBMS), and a reference station network previously developed by our group, we evaluate the urbanization effects on trends of the extreme temperature indices of the RCBMS for the time period 1961–2008. The following conclusions can be drawn from this study.

1) All the country-averaged annual- and seasonal-mean extreme temperature indices series for the RCBMS experience statistically significant trends, except for the increases in spring of the lowest Tmax and in summer of the highest Tmax. Larger and more significant trends occur in the indices series relative to minimum temperature and the largest positive annual trends are seen for the lowest Tmin and warm nights, reaching $0.596°\mathrm{C}\,(10\,\mathrm{yr})^{-1}$ and $8.584\,\mathrm{days}\,(10\,\mathrm{yr})^{-1}$, respectively. Decrease of cold nights in winter and increase of warm nights in summer are among the largest seasonal changes of the indices.
2) The annual-mean urbanization effect for mainland China as a whole is 0.070°, 0.023°, and $0.047°\mathrm{C}\,(10\,\mathrm{yr})^{-1}$, for Tmin, Tmax, and Tavg, respectively, all statistically significant at the 0.05 confidence level, with urbanization contributions being 18.4%, 10.1%, and 15.4%, respectively. Urbanization effects in winter and spring Tmin series are larger, reaching 0.083° and $0.072°\mathrm{C}\,(10\,\mathrm{yr})^{-1}$, respectively. Overall, seasonal-mean urbanization contributions for Tmin, Tmax, and Tavg range from 7.5% to 20.6%. The largest urbanization effects for annual-mean Tmin occur in north China, mostly ranging from 0.10° to $0.30°\mathrm{C}\,(10\,\mathrm{yr})^{-1}$, and the urbanization contributions generally from 20% to 60%.
3) Annual- and seasonal-mean urbanization effects for DTR in mainland China as a whole are all highly significant. The largest seasonal-mean DTR decline because of urbanization occurs in winter and spring, reaching $-0.061°$ and $-0.060°\mathrm{C}\,(10\,\mathrm{yr})^{-1}$ respectively, but the largest contributions appear in autumn and spring, being 58.1% and 35.9%, respectively. There is a spatially coherent distribution of the DTR urbanization effects across mainland China, and most of the regions experience a decrease because of urbanization. A 100% urbanization contribution is registered in a few areas of the country.
4) Annual extreme values of Tmin and Tmax experience upward trends because of urbanization, and more evident urbanization effects appear in the TNN and TNX series, but a larger interannual variability exists in the indices compared to Tmin, Tmax, Tavg, and DTR. Annual- and seasonal-mean urbanization effects for TNN are statistically significant. However, seasonal-mean urbanization effects for TXN and TXX for all the seasons are not significant. The larger urbanization effects for annual-mean TNN occur in north China and the northern Qinghai–Tibet Plateau. The urbanization effects for annual-mean TXN and TXX, however, are generally not significant.
5) The country-averaged annual-mean SU25, TR20, and FD0 series also see significant urbanization effects. The urbanization effects and contribution are $1.090\,\mathrm{days}\,(10\,\mathrm{yr})^{-1}$ and 37.8% for tropical nights, $-0.360\,\mathrm{days}\,(10\,\mathrm{yr})^{-1}$ and 10.1% for frost days, and $0.335\,\mathrm{days}\,(10\,\mathrm{yr})^{-1}$ and 12.8% for summer days. An insignificant urbanization effect has been detected for ice days over mainland China as a whole. Spatially coherent urbanization effects are seen for TR20 and FD0, with the TR20 urbanization effects mostly exhibiting significantly positive trends of 1.00–2.00 $\mathrm{days}\,(10\,\mathrm{yr})^{-1}$ in north China and southeastern China, and the FD0 urbanization effects showing significantly negative trends from -1.00 to $-3.00\,\mathrm{days}\,(10\,\mathrm{yr})^{-1}$ in north China.
6) Urbanization has led to a highly significant decline of annual-mean cold nights at a rate of

$-1.485\,\mathrm{days}\,(10\,\mathrm{yr})^{-1}$, accounting for 17.6% of the overall decrease as observed in the RCBMS, and a tremendous increase of annual-mean warm nights at a rate of $2.264\,\mathrm{days}\,(10\,\mathrm{yr})^{-1}$, accounting for 26.4% of the overall increase as observed in the RCBMS. The urbanization-induced decline of cold nights mainly occurred after 1972, but the increase in warm nights because of urbanization dominantly appeared after the early 1990s. Although the urbanization effects are also statistically significant for cold days and warm days, they are relatively smaller in magnitude. Seasonal-mean urbanization effects are statistically significant for the relative threshold indices and for all seasons except for the cold days and warm days of spring.

The negative (positive) TN10p (TN90p) urbanization effects are statistically significant for most regions, indicating the tremendous decrease (increase) in cold nights (warm nights) because of urbanization near the RCBMS. The largest urbanization effects for both TN10p and TN90p, usually ranging from 1.50 to $5.00\,\mathrm{days}\,(10\,\mathrm{yr})^{-1}$ for absolute values with urbanization contributions mostly from 20% to 60%, appear in north China, the mid-to-lower Yangtze basin, and the eastern part of the Qinghai–Tibet Plateau. Larger urbanization effects are in northern regions for TN10p, but in the south for TN90p. The annual-mean TX10p and TX90p urbanization effects exhibit generally less spatial coherence.

7) Except for DTR and the four relative threshold indices, the smallest absolute values of annual-mean urbanization effects or the annual differences of the ETIs between the RCBMS and reference stations in the country as a whole generally occur during the time period 1966–76. This is especially true for Tmin, Tavg, Tmax, TNN, TXN, TR20, and FD0. The 10-yr Cultural Revolution and the resulting deurbanization might have led to the abnormally small urbanization effects observed from the RCBMS. After that, urbanization effects rapidly and stably increased.
8) The urbanization effects reported for all the indices series in this paper should be regarded as the lowest estimates resulting from the compromise for selecting quality reference stations in a few areas in the country. It is therefore clear that urbanization effects on the long-term trends of the frequently used extreme temperature indices series of the observational data commonly applied in mainland China are of significance, despite the fact that they are generally smaller compared to the regional background changes, probably resulting from other factors and processes. The larger and more significant urbanization effects are especially notable for the indices related to daily minimum temperature in relatively developed areas of the country.

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