A Significant Bias of T_{max} and T_{min} Average Temperature and Its Trend

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ABSTRACT

The systematic bias of the estimated average temperature using daily T_{max} and T_{min} records relative to the standard average temperature of four time-equidistant observations and its effect on the estimated trend of long-term temperature change have not been well understood. This paper attempts to evaluate the systematic bias across mainland China using the daily data of national observational stations. The results revealed that the positive bias of annual mean temperature was large, reaching 0.58°C nationally on average; regional average bias was lowest in the northwest arid region and highest in the Qinghai–Tibetan Plateau; the bias was low in spring and summer and high in autumn and winter, reaching its lowest point in mid- and late May and highest point in early November. Furthermore, the bias showed a significant upward trend in the past 50 years, with a rising rate of 0.021°C $(10\,\mathrm{yr})^{-1}$, accounting for about 12% of the overall warming as estimated from the data of the observational network; the largest positive trend bias was found in the northwest arid region, while the east monsoon region experienced the smallest change; the most remarkable increase of the bias occurred after early 1990s. These results indicate that the customarily applied method to calculate daily and monthly mean temperature using T_{max} and T_{min} significantly overestimates the climatological mean and the long-term trend of surface air temperature in mainland China.

1. Introduction

Temperature is an indicator of thermal state that characterizes a warm or cold climatic condition and is one of the basic climatic variables. Accurately estimating daily mean temperature, however, is affected by the observations and the statistical methods used for calculating average temperature. To understand the possible effect of current observational practices and statistical methods on daily and monthly mean temperature estimates, therefore, has important significance for both climatological and climate change research (Brooks 1921; Edwards 1982; Tang and Ding 2007).

Currently, the T_{max} and T_{min} are more frequently shared in the international exchange data, and usually the daily mean temperature can be obtained by averaging the maximum and minimum temperatures (i.e., the max–min average method). Furthermore, several datasets of global land historical temperature primarily use the max–min average method to calculate the daily and monthly mean temperatures (Lawrimore et al. 2011; Jones et al. 2012; Morice et al. 2012; Sun et al. 2018). According to the *Specifications for Surface Meteorological Observation (2003)* of the China Meteorological Administration

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(CMA 2003), however, it is stipulated that the daily mean temperature of the national meteorological stations be calculated based on the average of 4 temperatures recorded at 0200, 0800, 1400, and 2000 Beijing time. This 4-time-observation average is the most frequently used average temperature in the national meteorological service and the scientific research works conducted in China (Tang and Ren 2005; Ren 2008; Li and Yan 2009; Cao et al. 2013).

In the studies conducted by Brooks (1921), Miller (1976), and Edwards (1982), it is shown that the annual and seasonal mean temperatures obtained using the max–min average method are generally higher than the mean temperatures estimated based on records at regular intervals like the 4-time-observation method. Additionally, Tang and Ren (2005) and Tang and Ding (2007) compared the monthly and annual mean temperature obtained from the max–min average method versus the temperature obtained from averaging four regular observations for eastern China and concluded that the difference in the temperature anomaly series and the rate of temperature increase was not significant. Moreover, Tang and Ren (2005) and Tang and Ding (2007) found that, when a large enough number of stations are used, the two methods were interchangeable. However, the research in China only used the observation data from a limited number of stations and focused on the influence of the estimation of temperature trends in the previous works; the systematic analysis of the error as calculated by using the max–min average method is lacking.

Some works have been focused on data homogenization and uncertainties (e.g., Thompson et al. 2008; Ren 2008; Jones and Stott 2011; Kennedy et al. 2011). Considering the inhomogeneities and uncertainties, however, the previous studies found, by using the monthly and annual mean temperature as an indicator, that global and regional climates had been in a significant warming trend (IPCC 2013; Carrasco 2013; Osborn and Jones 2014; Kothawale et al. 2010, 2016). This warming is characterized by an asymmetry between the maximum and minimum temperatures (Karl et al. 1993; Qian and Lin 2004; Rehman and Al-Hadhrami2012; Samba and Nganga 2014; Chen et al. 2007). The following problems remained, however: 1) what is the difference between the temperatures obtained from the max–min average method and from the average of 4-time-observation per day at equal intervals? 2) How does this difference (i.e., temperature bias), if it exists, vary spatially and seasonally? Finally, 3) how much does the bias affect the estimation for the trend of long-term temperature change? Currently, our understanding of these issues is insufficient both in China and around the world.

This study focuses on the three questions by taking China as an example. Using the observation data of daily and hourly temperature of the national reference climate and basic meteorological station network, the temperature bias in different regions and seasons, and its effect on the estimate of long-term change of temperature, was analyzed. The analysis results will provide new insights into the systematic errors of surface air temperature and its change as calculated from the max–min average method for studies of climatological and climate change.

2. Data and methods

a. Data collection

The daily data were from the National Meteorological Information Center, CMA. The Daily Dataset of China's Surface Climatic Data, version 3.0 (V3.0), contained the daily temperature data [the daily mean (4-time observations), daily maximum, and daily minimum records] of the Chinese national reference climate and basic meteorological stations since 1 January 1951. To ensure the accuracy of the observation records at stations and to avoid the analysis bias caused by the short-term absence of measurements at individual stations, only data from stations with complete records and consecutive observations were retained. Thus this study applied data of 719 stations with complete records ranging from 1964 to 2013. The data were quality controlled but not homogenized for possible inhomogeneities induced by relocation and instrumentation.

To examine the effect of homogenization on temperature bias and its trends, the homogenized data from monthly mean temperature based on 4-time observations (Li et al. 2004) and the maximum and minimum temperature data from the same 719 stations were also used [the China Homogenized Historical Temperature Dataset (CHHTD-V1.0)] to evaluate the difference of the results by using the two datasets. The distribution of the annual and monthly mean temperature biases were analyzed using both the raw and the homogenized data.

b. Methodology

To understand the long-term trend of temperature change, the correlation coefficient (i.e., trend coefficient) between temperature and time sequence of observational years was calculated according to the method outlined in Von Storch and Zwiers (2003) and Shi et al. (2003). The trend coefficients defined in this way are dimensionless and vary between $[-1, 1]$. This minimizes the effect of variance of meteorological variables and the unit on the numerical values of linear regression coefficients,

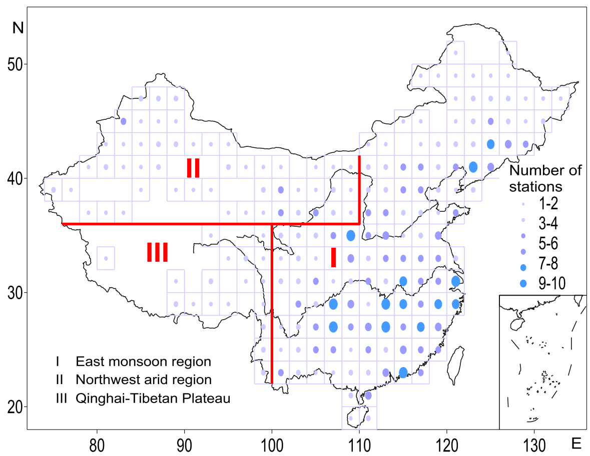

FIG. 1. Distribution of longitude–latitude boxes of 2.0° × 2.0° with observational stations, and the boundaries of three subregions. The values in the boxes are the numbers of stations. The three subregions: east monsoon region (region 1), northwest arid region (region 2), and the Qinghai–Tibetan Plateau (region 3).

and thus makes it easily comparable across geographical locations and suitable for studying the spatial characteristics of long-term trends of large-scale temperature change.

There were more stations distributed in the east than in the west. If regional average is calculated by simple arithmetic mean of all the sites with equal weights, then the data from the eastern region will outweigh that from the western region. To avoid this imbalance, the method by Jones and Hulme (1996) was utilized. According to this method, the average regional climatic time series are calculated by using an area-weighted average procedure.

The whole study region was divided into longitude–latitude boxes of 2.0° × 2.0°. A total 196 effective boxes with more than one station in each throughout mainland China was produced (Fig. 1). When calculating the national or regional average series, the arithmetic mean of the temperature recorded by the stations in each box was calculated first to obtain box averages; the cosine of the center latitude of each box was used as the weight coefficient and the regional average time series was then calculated by using the area-weighted average method.

The study region is divided into three subregions referring to G. Y. Ren et al. (2016): the east monsoon region (region 1), the northwest arid region (region 2), and the Qinghai–Tibetan Plateau (region 3). For the temperature analysis and the convenience of calculation, the boundaries of the three subregions were further simplified on basis of the previous studies (Ding et al. 2013; G. Y. Ren et al. 2016) (Fig. 1).

c. Statistical analysis

Following equation was used to calculate the temperature bias of the max–min average from the 4-time observation average:

$$T_d = T_{mn} - T_4, \tag{1}$$

where T_d is the temperature bias, T_{mn} is the average temperature calculated using the max–min average method, and T_4 is the average temperature obtained using the 4-time observations at 0200, 0800, 1400, and 2000 Beijing time; T_{dh} was defined as T_d based on the homogenized temperature data.

To address whether T_4 could be used as a criterion or reference temperature for evaluating the temperature bias, we compared the 24-h observation data (T_{24}) of 3 stations located in northern China (from east to west): Jixi, Beijing, and Urumqi stations. The deviation of T_4 relative to T_{24} (Table 1) was calculated. T_{24} is the daily mean temperature of 24-h observations (hourly means). The months January, April, July, and October were used as representatives for winter, spring, summer, and autumn, respectively.

The mean temperature values for T_4 and T_{24} were calculated for 2017; there were certain differences in these values. Namely, T_4 values of Beijing and Urumqi stations were lower than T_{24} with an accuracy of 10^{-2}°C (−0.043° and −0.077°C, respectively). The T_4 of Jixi station was higher than T_{24} with an accuracy of 10^{-3}°C (0.001°C). The T_4 of Beijing station was higher than T_{24} in spring with accuracy of 10^{-1}°C, but lower than T_{24} in other seasons, particularly in winter. The T_4 of Jixi station was lower than T_{24} in summer, but higher than T_{24} in other seasons. The T_4 of Urumqi station was higher than T_{24} in winter and lower than T_{24} in other seasons. However, the biases of T_4 relative to T_{24} were small overall, and the average annual mean absolute difference was well below 0.04°C, one magnitude of power lower than T_d as seen below. Therefore, the bias of the T_{mn} can be evaluated using T_4 as a benchmark. The reason for the applicability of the T_4 as standard to assess the uncertainty of T_{mn} will further discussed below.

The analysis period was from 1964 to 2013. The seasonal division was made using the definition of meteorological season. Winter included December of the previous year, and January and February; spring included March, April, and May; summer included June, July, and August; and autumn included September, October, and November. The seasonal mean temperature was calculated as the average of the 3 monthly mean temperatures in the season. The annual mean temperature was calculated as the average across the 12 months. Decadal means were also calculated, where

TABLE 1. Comparison of average difference between T_4 and T_{24} at three meteorological stations of northern China (Jixi, Beijing, Urumqi) in 2017.

Station	Latitude (°N)	Longitude (°E)	Altitude (m)	January (°C)	April (°C)	July (°C)	October (°C)	Annual (°C)
Jixi	45.3	130.92	272.5	0.000	0.074	−0.011	0.039	0.001
Beijing	39.8	116.47	31.3	−0.143	0.126	−0.019	−0.039	−0.043
Urumqi	43.78	87.65	935	0.020	−0.118	−0.137	−0.072	−0.077
Average				−0.041	0.027	−0.056	−0.024	−0.040

the first 10 years for decadal means ranged from 1964 to 1973, and the fifth decade ranged from 2004 to 2013.

The significance of linear trend in the analysis was examined by the correlation coefficient using the two tailed t-test method. Under the assumption that the correlation coefficient $p = 0$ is established, the probability density function of the correlation coefficient r is the density function of the t distribution, and the statistic

$$t = \mathrm{sqrt}(n-2)r/\mathrm{sqrt}(1-r^2) \tag{2}$$

follows a t distribution with a degree of freedom (d.f.) $n - 2$. Given a significance level α, and if $t \geq t_\alpha$, the correlation coefficient is considered significant. The linear trend of α over 0.05 (0.01) significance level was expressed as $p \leq 0.05$ (0.01).

3. Results

a. National and regional average T_d

The analysis results for annual and seasonal mean T_d for the country and different regions are shown in Table 2. The T_d values were positive in every season of every region of mainland China. The national average annual mean T_d was 0.58°C. The average T_d was the highest in region 3 (0.85°C), and the lowest in region 2 (0.47°C). In all seasons, the average T_d values in region 3 were the highest, with the maximum value in autumn (1.07°C). In spring and summer, the T_d values of region 2 were the lowest (0.21° and 0.27°C, respectively). The annual and seasonal mean T_d values of region 1 were close to the national averages. The values of autumn and winter were relatively high, while the spring and summer were lower.

b. Spatial distribution of T_d

T_d values were positive in most parts of the country, indicating a universally higher average of the T_{mn} than that of T_4 (Fig. 2). The areas with a high T_d value were located in the eastern part of the Qinghai–Tibetan Plateau (region 3) and the Sichuan basin and the Yunnan–Guizhou Plateaus, where T_d was greater than 1.00°C. The highest values were found at Malcolm of Sichuan (1.85°C) and Mengla of Yunnan (1.62°C). The T_d values of regions 2 and 1 were relatively low (less than 0.4°C). Only two stations in the whole study region showed a small negative T_d (i.e., the T_{mn} is lower than that of T_4). They were Shiquanhe station in Tibet (−0.09°C) and Kumux station in Xinjiang (−0.04°C).

All national average seasonal mean T_d values were positive for each season, with the lowest value in the spring (0.43°C) followed by the summer (0.46°C) (Fig. 3). The autumn mean T_d value was the highest (0.74°C), followed by the winter (0.71°C). In the areas south of 30°N in mainland China, T_d was positive for all seasons. The areas with high seasonal mean values were found in the eastern part of the Qinghai–Tibetan Plateau (region 3), where the autumn and winter mean T_d was higher than those of other seasons (2.21° and 2.01°C, respectively), indicating a very large bias of seasonal mean T_{mn}. There were no negative T_d values in the winter for the whole country; negative T_d values only appeared in western Tibet in the autumn (−0.20°C), and in western Tibet and northern China in the spring and summer (−0.44° and −0.37°C, respectively).

c. Seasonal variation of T_d

Figure 4 shows the within-year variations in daily mean T_d averaged for 30 years of 1981–2010 in mainland China and the three subregions. The daily mean T_d series, starting from 1 January, experienced a decrease–increase–decrease variation within a year (Fig. 4). In late January, the T_d value in region 3 was noticeably lower, while the T_d values in region 1 and 2 did not notably decrease. The T_d values of region 1 and 2 rapidly decreased in

TABLE 2. Regional average annual and seasonal mean T_d for mainland China and the three subregions (1981–2010) (unit: °C).

	East monsoon region (region 1)	Northwest arid region (region 2)	Qinghai–Tibetan Plateau (region 3)	Mainland China
Spring	0.46	0.27	0.61	0.43
Summer	0.49	0.21	0.85	0.46
Autumn	0.69	0.71	1.07	0.74
Winter	0.68	0.69	0.88	0.71
Year	0.58	0.47	0.85	0.58

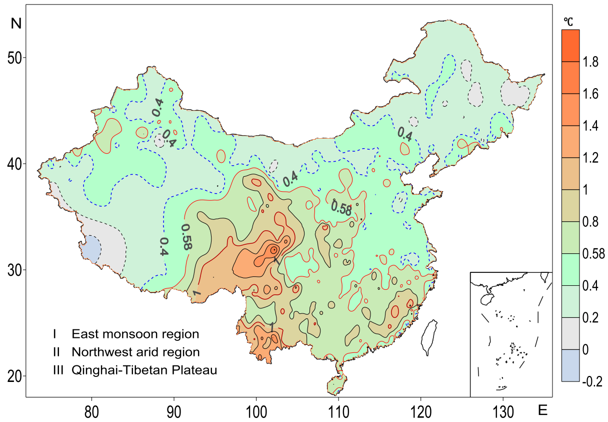

FIG. 2. The spatial distribution of annual mean T_d in mainland China (1981–2010) (red line = 0. 58; blue line = 0.40; brown = 1.00) (unit: °C).

mid-February and this decrease continued through mid- and late May. The T_d value of region 3 stopped decreasing in late February to early March, when it began to slightly increase. This increase continued through late September when there was another noticeable decline. The T_d values of region 1 and 2 rose at the beginning of June, peaked in early November, and then decreased. The T_d of region 2 declined relatively quickly from April to May, showing a large fluctuation in the bias of T_{mn}. The T_d of region 3 also showed a large fluctuation in February and December.

It is also notable from Fig. 4 that the differences of daily mean T_d among the three subregions were generally small during winter, but large during spring and early summer. The largest difference appeared between region 2 and region 3 from late April to early June, reaching 0.70°C, and the smallest difference was seen between region 1 and region 2 during wintertime. In addition, a larger variability of daily mean T_d was obvious in region 2 during period of mid- to late April.

d. The long-term change of T_d

From 1964 to 2013, both annual mean T_{mn} and T_4 in mainland China showed a significant upward trend, as shown in Fig. 5. The temperature increase rate of annual mean T_{mn} is 0.318°C $(10\,\mathrm{yr})^{-1}$ (d.f. = 48, $t = 8.167$, $p = 0.001$), and the annual mean T_4 increase at a rate of 0.297°C $(10\,\mathrm{yr})^{-1}$ (d.f. = 48, $t = 8.167$, $p = 0.001$).

It is also clear from Fig. 5 that all annual mean T_d values were positive from 1964 to 2013 and exhibited a significant upward trend with a rising rate of 0.021°C $(10\,\mathrm{yr})^{-1}$ (d.f. = 48, $t = 9.653$, $p = 0.001$). Since the beginning of the twenty-first century, this increase has become more notable and the annual mean T_d was

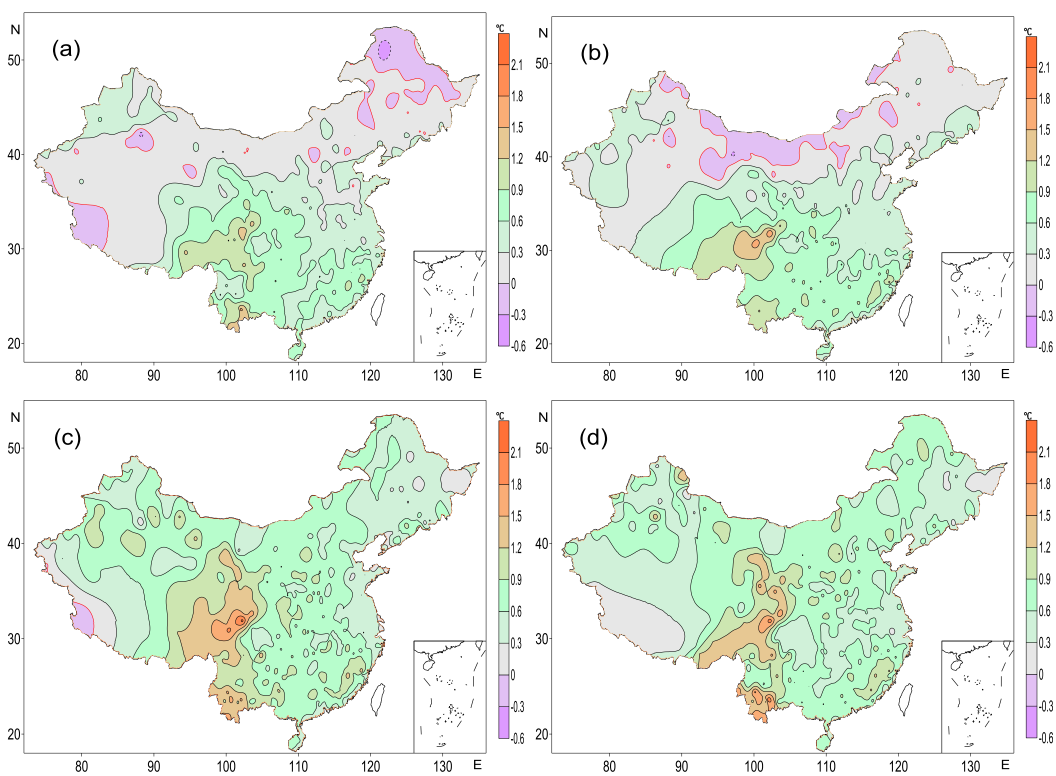

FIG. 3. Spatial distribution of seasonal mean T_d in mainland China (1981–2010): (a) spring, (b) summer, (c) autumn, and (d) winter (unit: °C).

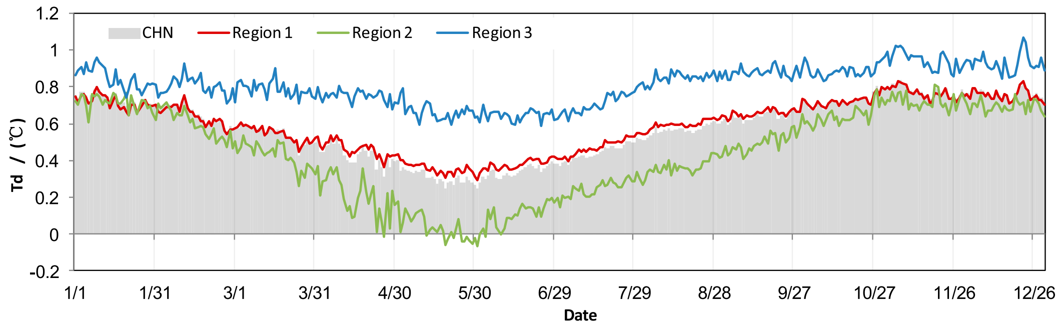

FIG. 4. The seasonal variation of daily mean T_d in mainland China and the three subregions (1981–2010): 1/1 denotes 1 Jan and 12/26 denotes 26 Dec. CHN: mainland China. Region 1: east monsoon region; region 2: northwest arid region; region 3: Qinghai–Tibetan Plateau.

higher than the average from 1981 to 2010. After 2008, however, the T_d underwent a slight decrease, but it rose again in 2013 with a historical maximum value (0.63°C) registered.

The annual mean T_d values of all 3 subregions were positive and exhibited significant upward trends from 1964 to 2013 (Fig. 6). The most apparent increase appeared in the twenty-first century, when all T_d values were above the 30-year average. The highest rising rate was in region 2 [0.027°C $(10\,\text{yr})^{-1}$, d.f. = 48, $t = 8.810$, $p = 0.001$], followed by region 3 [0.022°C $(10\,\text{yr})^{-1}$, d.f. = 48, $t = 5.259$, $p = 0.001$]. In contrast, the rising rate of T_d in region 1 was lower [0.018°C $(10\,\text{yr})^{-1}$, d.f. = 48, $t = 9.097$, $p = 0.001$].

Figure 7 shows that, for each season, the T_d value of region 3 was the highest, and the seasonal mean values were 0.61°, 0.85°, 1.07°, and 0.88°C for spring, summer, autumn, and winter, respectively (Fig. 7). In the summer, the T_d value of region 3 was 0.64°C higher than region 2, and 0.36°C higher than region 1. All of the seasonal mean T_d values in the three subregions and in the country as a whole showed upward trends during 1964–2013, with the most obvious increases generally occurring after 2000. In the autumn, the T_d value of region 3 was 0.36°C higher than region 2, and 0.39°C higher than region 1. The possible causes for the accelerated increase in more recent years needs to be further examined, but it may have been related to the more widespread urbanization, which will result in a greater increase in $T_{\min}$ in the north and in $T_{\max}$ in the south (Ren and Zhou 2014), or the alleviated air pollution (Wang and Yang 2014; Lowsen and Conway 2016), which leads to a more rapid increase in $T_{\max}$.

The linear trend and significance test results of seasonal mean T_d in different subregions and in mainland China on a whole are shown in Table 3. There was a significant increasing trend in annual and seasonal mean T_d for the 3 regions and for mainland China as a whole, except for winter for region 1, region 2, and the whole region (Table 3). The maximum linear increasing trend was found for summer in region 1 and region 2, whereas in region 3, it appeared in spring. In view of annual mean temperature, the increasing bias shown in Table 3 accounts for about 12% of the overall

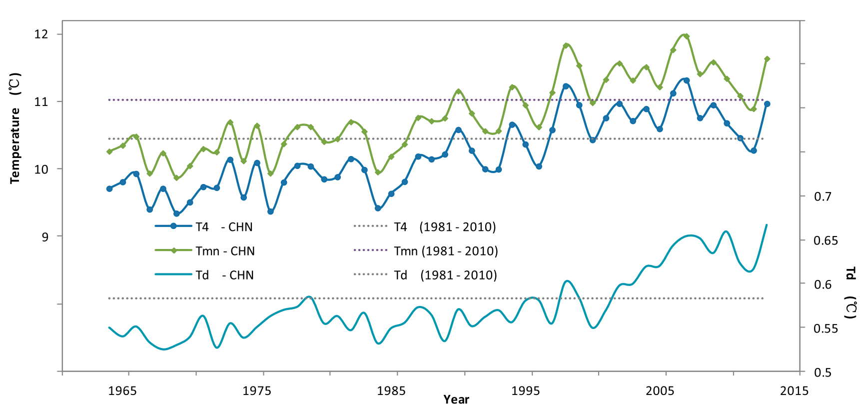

FIG. 5. Change in national average annual mean T_4, T_{mn}, and T_d values in mainland China during 1964–2013 (unit: °C). CHN: mainland China.

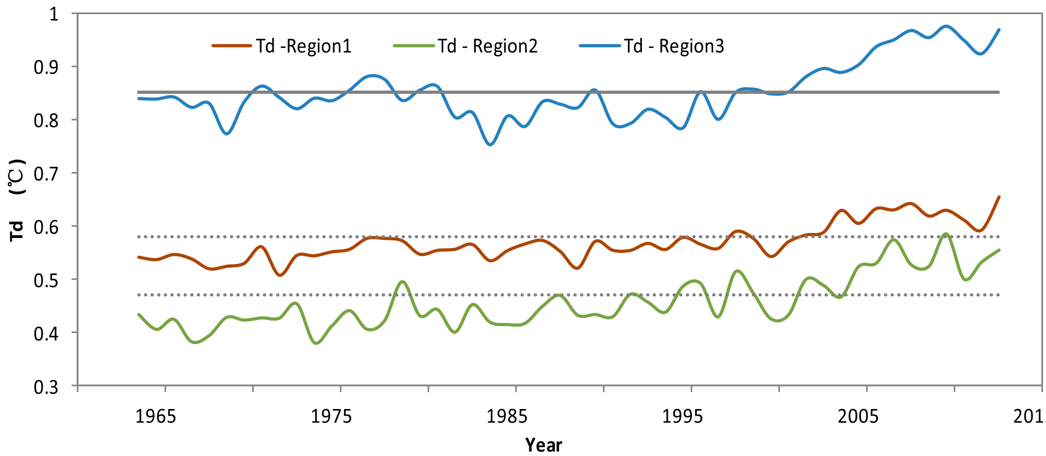

FIG. 6. Change in regional average annual mean T_d values in different subregions of mainland China during 1964–2013 (unit: °C). Region 1: east monsoon region; region 2: northwest arid region; region 3: Qinghai–Tibetan Plateau.

warming as estimated from the data of the national observational network.

4. Discussion

Previous studies pointed out that the daily and monthly mean temperature values obtained from the max–min average method show some differences from the ''real'' average temperature (Brooks 1921; Miller 1976; Edwards 1982; Tang and Ren 2005; Tang and Ding 2007). Therefore, there is certain bias of the daily and monthly mean temperature as calculated from the daily T_{max} and T_{min} records. In this study, the magnitude and detailed spatial–temporal pattern of the bias, and in particular the trend of its long-term change, were analyzed with the mainland China as an example.

The analysis revealed that the daily mean temperature value obtained from the max–min average method was warmer than the standard 4-time observation average. The national average annual mean T_d reached 0.58°C, with the Qinghai–Tibetan Plateau (region 3) as large as 0.85°C. The average T_d of autumn and winter were even higher. The analysis results also showed that the annual and seasonal mean T_d values exhibited a significant upward trend from 1964 to 2013, with the rate of increase in mainland China average annual mean T_d reaching 0.021°C $(10\,\mathrm{yr})^{-1}$. The trends of increase in three subregion average annual and seasonal mean T_d was also significant, with the exception for winter.

Overall, the T_{mn} average values were higher than the T_4 or T_{24}. This is because the former only has two observational points in a day, before sunrise and in the afternoon (at about 0600 and 1400 Beijing time near 120°E in spring and autumn, respectively). The two observational points are separated by only 8 h, with the records of 0200 and 2000 Beijing time in the T_4 absent (Fig. 8). They are therefore more affected by the daytime surface heat condition and especially the impact of the hottest afternoon period, but they escape in a larger extent from the effects of ground thermal conditions of nighttime when the surface air is colder than the daytime.

In the eastern part of northeast China and western China, the daily T_{max} and T_{min} occur slightly earlier or later than those in Beijing. In western China, the T_{max} and T_{min} occur 3 h later at most than those in Beijing. The interval between the occurrence of the T_{max} and T_{min} does not increase. Therefore, the T_{mn} values still have large biases in terms of daily mean temperature in these regions far away from the meridian of 120°E. The impact of time difference between east and west of the country on T_4 and T_{24} would be minor, because the four times of observations are made with an equal interval (6 and 1 h) in a day.

Additionally, climatic conditions of the observational stations may have an effect on the T_d value (Fig. 9). The other factors that could affect the T_d value include humidity, wind speed, elevation, and precipitation days (Fig. 9). Precipitation day refers to the day with precipitation greater than or equal to 0.1 mm from 0800 to 0800 Beijing time. Clearly, the annual mean T_d values show a positive correlation with relative humidity (r = 0.30), elevation (r = 0.32), and precipitation days (r = 0.53). The T_d values exhibit a significant negative correlation with the average wind speed (r = −0.51). In regions with higher relative humidity and more precipitation days, the T_d values were larger. The T_d values were also large in the high-elevation areas, and in regions that had a small annual mean wind speed.

The T_d values were larger in areas with high humidity and more precipitation days. This is likely related to the abundance of atmospheric moisture in these areas and a

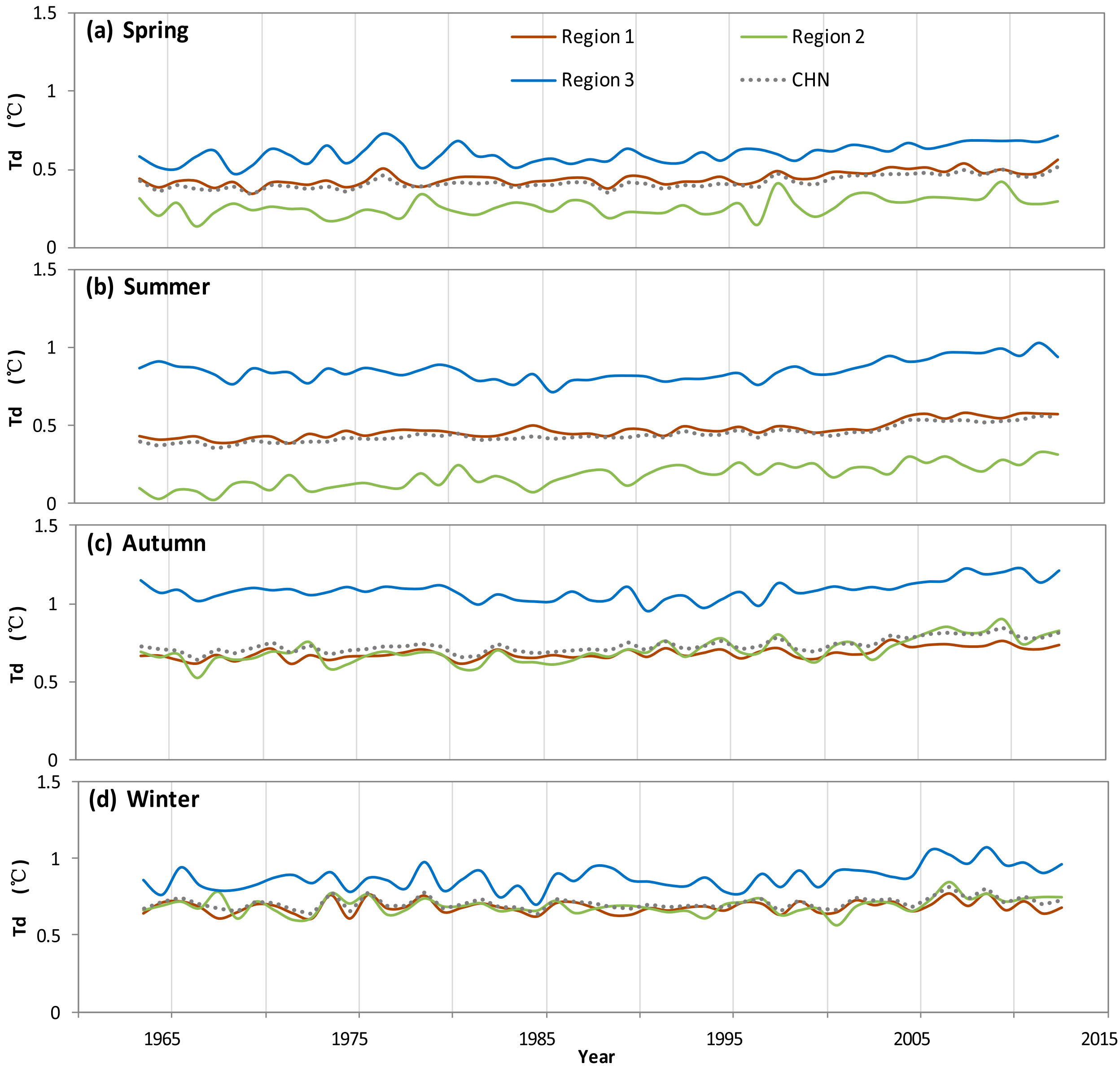

FIG. 7. Change in seasonal mean T_d values in mainland China and the different subregions during 1964–2013: (a) spring, (b) summer, (c) autumn, and (d) winter) (unit: °C). Region 1: east monsoon region; region 2: northwest arid region; region 3: Qinghai–Tibetan Plateau.

high cloudiness. Higher atmospheric relative humidity and cloudiness at the coldest stage of the early morning can cause the minimum temperature to be higher due to the trapping effect of the longwave radiation from the surface, leading to a greater T_d value. Particularly, in South China, southwest China, the eastern Qinghai–Tibetan Plateau, and in other areas with high humidity and a high number of precipitation days, the night rain rate is usually high (Yu et al. 2007; Duan et al. 2013). This is conducive to raising the minimum temperature in the early morning and at the same time does not significantly reduce the afternoon maximum temperature, increasing the T_d value. The T_d values showed a negative correlation with the annual mean wind speed, possibly because near-surface turbulence and convection are stronger when daytime wind speed is high, which helps the heat to be diffused. This is unfavorable to the afternoon maximum temperature rise and causes the max–min average values to be low.

The T_d value is generally large in a high-elevation area, but the correlation with elevation is not significant and the reasons for this need to be investigated further. One possible reason may be that the humidity and cloudiness of high-elevation areas are also high; cloudiness is high when the surface air reaches its lowest

TABLE 3. Linear trends and significance test results of annual and seasonal mean biases (T_d) in mainland China and the three subregions (1964–2013). Asterisk (*) indicates significant at $p = 0.05$ level. CHN: mainland China.

Linear trend [°C (10 yr)$^{-1}$]	East monsoon region	Northwest arid region	Qinghai–Tibetan Plateau	CHN
Spring	0.022*	0.018*	0.022*	0.021*
Summer	0.029*	0.044*	0.021*	0.032*
Autumn	0.017*	0.035*	0.017*	0.021*
Winter	0.005	0.008	0.027*	0.008
Year	0.018*	0.027*	0.022*	0.021*

temperature in early morning but sunshine is sufficient in the afternoon, resulting in a significantly higher T_{mn} value. This is especially true in eastern parts of the Qinghai–Tibetan Plateau (Yu et al. 2007; G. Y. Ren et al. 2016). However, the western Qinghai–Tibetan Plateau has fewer precipitation days and a drier climate, and this may be one of the reasons why the correlation of T_d with elevation is not significant in mainland China on a whole.

From 1964 to 2013, there was a significant upward trend in the national and regional average annual and seasonal mean T_d, which may be related to the ''asymmetric'' change of the diurnal temperature. In most regions of mainland China, T_{max} and T_{min} rose in the past half-century, but T_{min} rose much faster than T_{max} (Zhai and Ren 1997; Ren and Zhou 2014), which may have caused the T_d value to rise continuously relative to the trends of the standard T_4 or T_{24}. A recent study applying hourly mean temperature data also showed that, since the early 1970s, the most rapid surface air temperature rise in a day occurs around sunrise and early morning, especially between 0600 and 1400; temperature rise slows in the afternoon and most of the night (Y. Y. Ren et al. 2016). Therefore, the minimum temperature, and the maximum temperatures in less extent, occurs at time when the most rapid warming is experienced in a day, resulting in a significant increase in annual and seasonal mean T_d over time. Moreover, the cause of the asymmetry in diurnal temperature change may be related to the effects of urbanization and the effect of aerosols around the observational grounds of the stations (Ren and Zhou 2014; Y. Y. Ren et al. 2016).

Although the data used in this paper were quality controlled, they were not processed for homogenization. The inhomogeneities of the observational data were likely caused by the relocation of stations and the change of instruments. T_d values thus may be affected by the inhomogeneities of data. To understand this effect, the difference between the homogenized data from 719 stations and the results of this study were calculated and analyzed. The homogenized temperature data were developed by Cao et al. (2016). The inhomogeneities in individual station series were detected by using a penalized maximum t test (PMT) that accounted for the first-order autocorrelation. Detailed metadata information was applied to validate the breakpoints caused by changes in the observational sites and instruments. The quartile-matching (QM) method was applied to adjust the discontinuities caused by the nonclimate changes.

The difference between the annual mean T_{dh} (bias of T_{mn} as calculated based on homogenized data) and T_d as given above is shown in Fig. 10. The differences were positive in 2013 only and negative in all previous years. In general, homogenization of data reduced T_d, but the change was in the accuracy range of 0.01°C. This indicates that the bias of the homogenized data is slightly lower, but the difference is very small, showing a negligible effect of homogenized data on the estimate of the bias of average T_{mn}. In view of the long-term trend of the bias, however, the data homogenization increased T_d trend (d.f. = 48, t = 8.026, p = 0.001), indicating that the present analysis actually underestimated the increasing trend of the temperature bias of T_{mn}. If the homogenized data are used, therefore, the rate of the increased T_d with time will become larger.

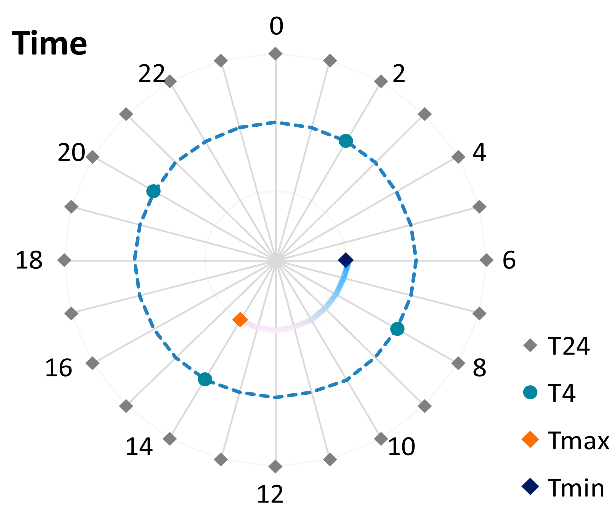

FIG. 8. A schematic diagram of distribution of observational points in the day for the maximum and minimum temperature (T_{max}, T_{min}), 4-time fixed intervals (T_4), and 24-time fixed intervals (T_{24}).

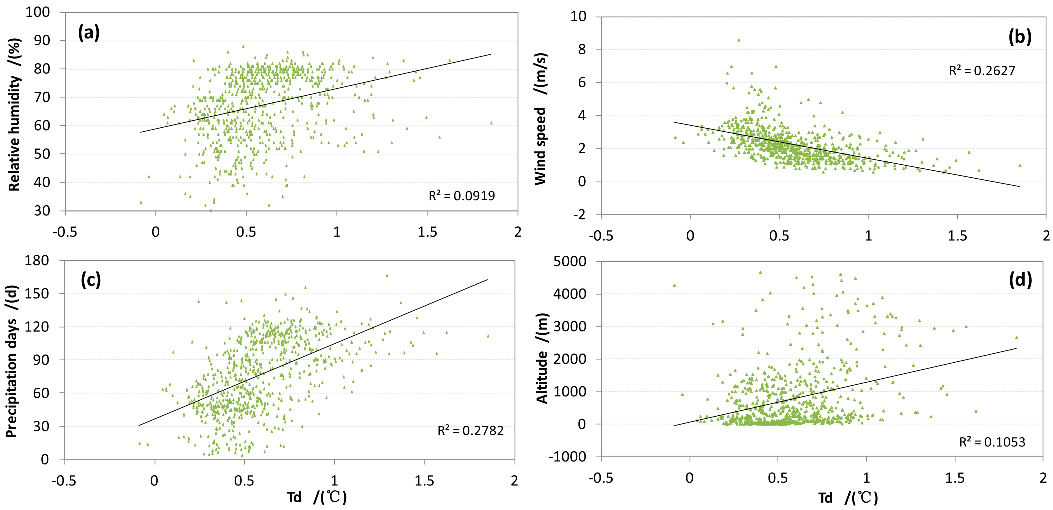

FIG. 9. Relationship of annual mean T_d with meteorological variables: (a) relative humidity, (b) wind speed, and (c) precipitation days; and geographical variable (d) altitude, in mainland China.

The results of this paper are of significance for understanding the uncertainties in studies of climatology and climate change. In climatological studies and climate prediction, the use of T_{mn} generally causes a higher daily and monthly mean temperature than T_{24} or T_4 in mainland China, and probably in other subcontinental regions of the world. In some regions of the country, the bias even reaches 1.00°C in certain seasons. This requires a careful consideration or adjustment when more accurate analysis and prediction are needed.

In monitoring and studies of climate change, the annual and seasonal mean temperature is usually calculated and analyzed by using the max–min average method due to the difficulty in acquiring 4-time equal interval observation data, let alone the 24-times-a-day observations. It was found in this study, however, that annual and seasonal mean T_d has a significant increasing trend over time, and if the homogenized temperature data series is used, the upward trend will be greater. This shows that the average warming trend in mainland China, and probably in other large regions of the world, is generally overestimated by using daily and monthly mean temperature data as calculated from daily T_{max} and T_{min} records. If the homogenized temperature data are used, the overestimate will be a little larger.

These findings are novel and have practical significance. In China, it was a usual practice to use the daily and monthly mean temperature as calculated from 4 records at 0200, 0800, 1400, and 2000 Beijing time to analyze the long-term change in surface air temperature. However, the method was changed in analyzing change trends of temperature over time periods longer than the last 50–60 years. The long data series include the early instrumental records with different observational time in a day, which had been found to result in data inhomogeneities. In this case, a suggestion was made to use the max–min average method to avoid the possible breakpoints in data series (Tang and Ren 2005; Cao et al. 2013; Ren et al. 2017). It is obvious from this analysis that the max–min average method diminishes the effect of inhomogeneities

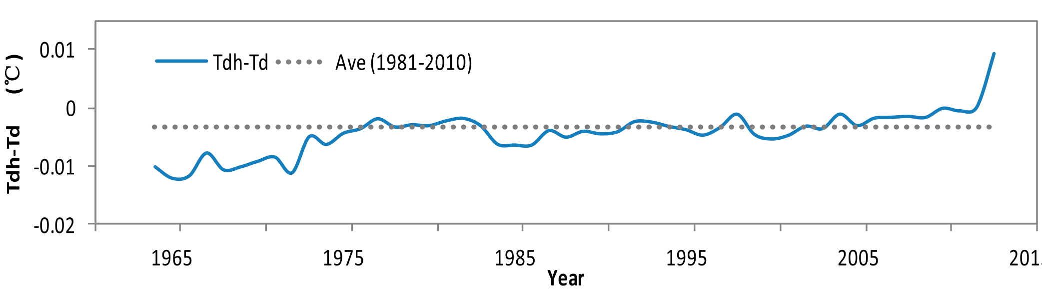

FIG. 10. Effect of data homogenization on temperature bias of the max–min average (T_d) as estimated based on the same observational station network in mainland China. Shown in the figure is the difference of country-averaged annual mean biases of the max–min average temperature between homogenized and nonhomogenized data.

on data series in some extents, but it at the same time significantly overestimates the warming trend of the past decades in mainland China. This overestimate becomes even more serious when homogenized data of the max–min average method based monthly mean temperature are applied.

Most of the previous studies of global land surface air temperature change also utilized the data of daily and monthly mean temperature as estimated by $T_{\max}$ and $T_{\min}$ (i.e., the max–min average method) (Lawrimore et al. 2011; Jones et al. 2012; Sun et al. 2018). It is unclear whether or not, or in what extents, the global land analyses based on monthly mean data, which mostly applied the daily mean temperature of $T_{\max}$ and $T_{\min}$ (or T_{mn}), have overestimated the past temperature increasing trends. However, the case from mainland China that has a diverse climate types and a vast territory indicates a need to further address this issue in future studies.

If this issue is nonignorable in global land, or the large deviations in the average temperatures and linear trends as calculated using the max–min average method exist in the current global land surface air temperature datasets, then there is an urgent need to adjust the daily and monthly observational data and the estimations of temperature trends based on them, and also to revise the data submission agreement by World Meteorological Organization (WMO) for the future operation and research of climate and climate change.

5. Conclusions

The bias of the average temperature estimated (T_d) using daily $T_{\max}$ and $T_{\min}$ records, including its temporal and spatial variation were analyzed using daily temperature data from 719 stations in mainland China. The following conclusions were drawn:

1) Starting in January, the daily mean T_d experienced a decrease in January, an increase after June, and a decrease once again after November. Generally, the T_d value was relatively large in autumn and winter, with the largest value occurring in early November, and it was relatively low in spring and summer.
2) T_d was positive in most areas, with larger values in the eastern part of the Qinghai–Tibetan Plateau, the Sichuan basin and the Yunnan–Guizhou Plateau (>1.0°C). The lowest T_d values were found in northwest and northeast China (0°–0.4°C).
3) There was a significant upward trend of annual mean T_d over time [0.021°C $(10\,\mathrm{yr})^{-1}$]. The three subregions were all showed a significant increase. The highest rising rate of annual mean T_d was in northwest arid region [0.027°C $(10\,\mathrm{yr})^{-1}$].
4) The T_d value of each season in the areas south of 30°N was positive. Negative values appeared only in western Tibet in autumn and in northern China in spring and summer. The increase of the seasonal mean T_d was generally largest in the summer.
5) With the homogenized data, the T_d values were lower, but the trend of T_d increased more significant over time. The analysis of the long-term surface air temperature change by using the monthly mean homogenized temperature data thus result in a further overestimate of warming trend.

Overall, the present analysis indicates that the previously applied method to calculate daily and monthly mean temperature using $T_{\max}$ and $T_{\min}$ significantly overestimates not only the climatological mean of the national stations and mainland China on a whole, but also the upward trends of surface air temperature at most of the stations and in the country. In particular, because the data of monthly mean temperature as calculated using $T_{\max}$ and $T_{\min}$ have been widely used in studies of long-term change in global land and regional average surface air temperature, the biases as revealed in this work should be carefully considered in future studies.

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