An Integrated Procedure to Determine a Reference Station Network for Evaluating and Adjusting Urban Bias in Surface Air Temperature Data

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ABSTRACT

Trends in surface air temperature (SAT) are a critical indicator for climate change at varied spatial scales. Because of urbanization effects, however, the current SAT records of many urban stations can hardly meet the demands of the studies. Evaluation and adjustment of the urbanization effects on the SAT trends are needed, which requires an objective selection of reference (rural) stations. Based on the station history information from all meteorological stations with long-term records in mainland China, an integrated procedure for determining the reference SAT stations has been developed and is applied in forming a network of reference SAT stations. Historical data from the network are used to assess the urbanization effects on the long-term SAT trends of the stations of the national Reference Climate Network and Basic Meteorological Network (RCN+BMN or national stations), which had been used most frequently in studies of regional climate change throughout the country. This paper describes in detail the integrated procedure and the assessment results of urbanization effects on the SAT trends of the national stations applying the data from the reference station network determined using the procedure. The results showed a highly significant urbanization effect of 0.074°C $(10\,\mathrm{yr})^{-1}$ and urbanization contribution of 24.9% for the national stations of mainland China during the time period 1961–2004, which compared well to results that were reported in previous studies by the authors using the predecessor of the present reference network and the reference stations selected but when applying other methods. The authors are thus confident that the SAT data from the updated China reference station network as reported in this paper best represented the baseline SAT trends nationwide and could be used for evaluating and adjusting the urban biases in the historical data series of the SAT from different observational networks.

1. Introduction

Monitoring and detecting climate change requires reliable historical data from surface observations. In particular, the quality and reliability of surface air temperature (SAT) data are critical for understanding the magnitudes and rates of climate warming in varied spatial scales. Defects and insufficiencies exist in the available observational SAT datasets, however, that need to be addressed carefully. These, among other concerns, include the sparseness of early period records and having SAT data series of sufficient length; data inhomogeneities caused by relocation, changes in instrumentation, and other shifts in observational practices; and the urbanization effects on SAT trends for stations near cities and towns.

The sparseness of early observations has been taken into consideration in large-scale analyses, and the inhomogeneities in SAT data have also been sufficiently addressed in most studies. Hansen et al. (1999, 2010), Jones et al. (2012), and the U.S. National Climatic Data Center (Karl et al. 1995; Easterling et al. 1996; Peterson et al. 1998; Lawrimore et al. 2011), for

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example, have all taken into account the uneven station distribution across the continents and the data inhomogeneities in constructing and analyzing their global mean SAT series, and other studies into regional mean SAT series have also attached importance to these issues (e.g., Karl et al. 1995; Wang et al. 1998; Ren et al. 2005; You et al. 2012; Hausfather et al. 2013; Chrysanthou et al. 2014). The possible systematic biases due to the urbanization effect, however, have not been adequately addressed, and arguments on the nature and magnitude of the urbanization effects for global and continental-scale SAT change studies have not been completely settled (Hughes and Balling 1996; Houghton and Ding 2001; Kalnay and Cai 2003; Vose et al. 2004). On subcontinental and regional scales, however, urbanization, which includes the intensifying urban heat island (UHI) effect, has been proved to exert significant impacts on SAT records and trends at many of the weather stations as well as on the regional mean SAT series, including those reported for mainland China and other regions of East Asia (Ren et al. 2005, 2007, 2008; Pielke et al. 2007a,b; Hua et al. 2008; Fujibe 2009; Zhang et al. 2010; Yang et al. 2011; Das et al. 2011; Stocker et al. 2013).

A major reason for the decades-long debates on the urban biases in large-scale land SAT series is related to the difficulty in determining the reference or rural stations, which do not have equivalent length of records relative to the urban stations (Hansen et al. 1999; Ren et al. 2008; Ren and Ren 2011; Fujibe 2011; Yang et al. 2011). Given the same time periods and regions analyzed and the datasets used, the polarization of the conclusions drawn on urban biases mostly results from the different criteria for the selection of the reference stations in the studies using the method of comparing urban and reference station series, which are generally regarded as the most reliable way to examine the urban biases (Jones et al. 1990; Trenberth 2004; Peterson and Owen 2005; Brohan et al. 2006; G. Ren et al. 2008, 2010). The usage of nonrepresentative reference stations, usually those in or near small cities and towns, inevitably causes underestimation of the urbanization effects in this regard (Karl et al. 1988; Ren et al. 2005, 2008).

Therefore, the arguments on the urban biases of land SAT series on the continental and global scales need to be settled, and the urban biases of land SAT series recognized at single sites or on regional scales need to be adjusted so that the more reliable data are available for use in analyses of climate change. Without such a solution to the issue, it is impossible to establish a global or regional SAT series that realistically represents the changes in large-scale temperature fields, and a convincing conclusion is less likely to be drawn from the studies of regional or global climate change detection and attribution.

To do that, it is necessary to first select representative reference SAT stations as a benchmark. This requires developing a more sophisticated procedure than those applied before. Many efforts have been made to develop new methodologies for the urban–rural analyses in the past decades. A frequently applied method is to determine the reference stations simply based on the total population or population density of the settlements where the stations are located (Jones et al. 1990; Zhao 1991; Portman 1993; Wu et al. 1994; Peterson et al. 1999; Hansen et al. 1999; Li et al. 2004b). Different criteria for population were used, however, and this led to a wide range of sizes of settlements being defined as rural. Obviously, remnant UHI was likely to exist in the SAT series of the reference stations when the population of the settlements was lower than a certain threshold (Karl et al. 1988; Oke 1973, 2004; Ren et al. 2008; Yang et al. 2011) and the observational grounds were still located near the centers of the towns or small cities, leading to an underestimated urban bias for the urban stations or any observational networks targeted in the studies. An improvement to the method involved considering not only the population of the settlements, but also the specific locations of the stations relative to the centers of the towns and small cities based on information gathered from large-scale maps and satellite pictures (Zhou and Ren 2005; Ren et al. 2008).

Night-light intensity from satellites was used to identify urban and rural stations (Peterson et al. 1999; Hansen et al. 2001; Ren and Ren 2011; Yang et al. 2011). This procedure would be better for application within a country or region. Incomparability would be obvious, however, when it was applied across continents or the globe, as a result of the varied social development levels, as well as the radically different cultures and traditions among the countries and regions. A Chinese city with similar magnitude of population and UHI intensity to that of a U.S. city would usually look much darker from the night-light imagery. Landsat-based land-use images were used by Y.-J. Yang et al. (2013) to categorize urban, suburban, and rural stations in China's Anhui Province, with reference to the proportion of different land-use types in 2-km-radius buffer zones around the stations, referring to that suggested by G. Ren et al. (2010). The satellite-based method of classification of stations is promising for applications for larger spatial scales if the influence of the land-use changes outside the buffer zones is also considered (Ren and Ren 2011; Y.-J. Yang et al. 2013; Wang and Ge 2012; He et al. 2013). Ren and Ren (2011) adopted the surface brightness temperature retrieved from remote sensing MODIS data and the specific locations of weather stations in the surface thermal fields to determine reference stations and urban

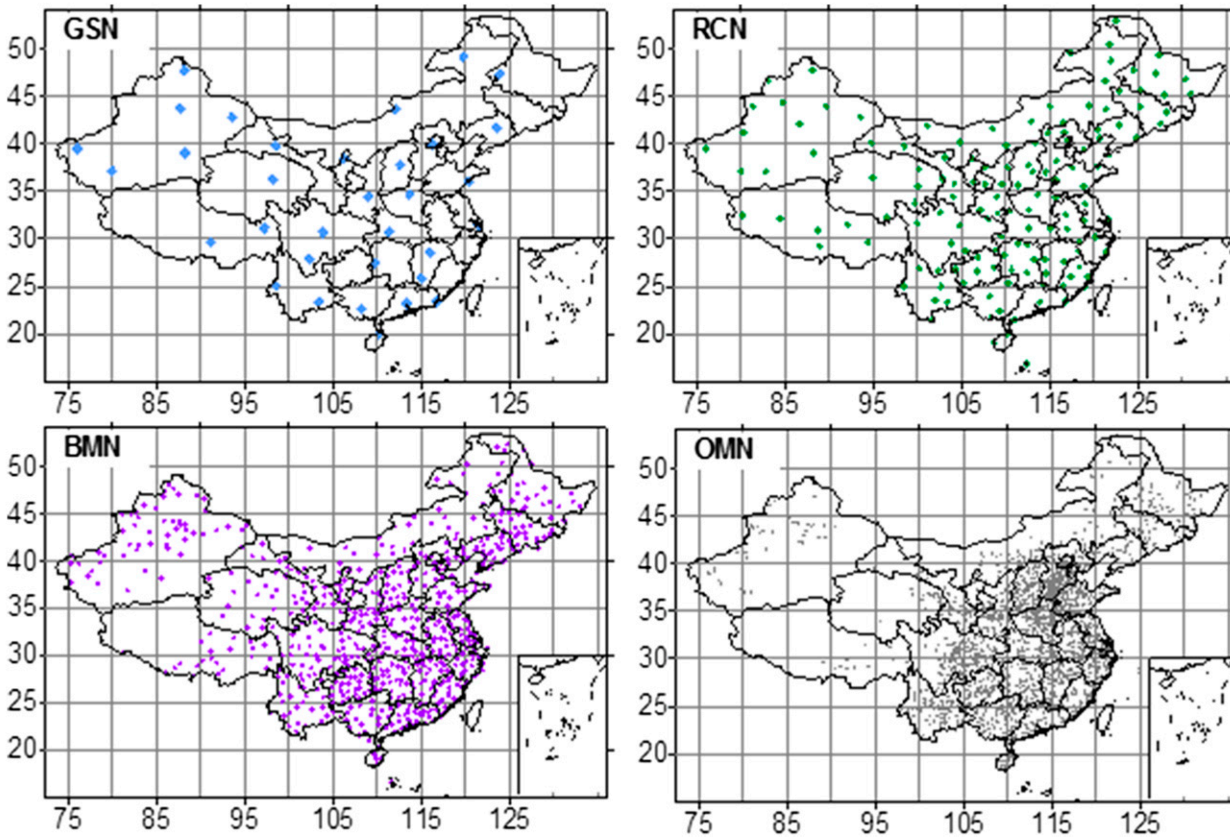

FIG. 1. Distribution of stations at various observation networks with historical records >50 yr in 2012 across mainland China, as defined in the text.

stations, which had been proven to be effective in mainland China, and would be potentially applicable in the global continents and islands.

A comprehensive method of selecting reference stations for mainland China was developed by G. Ren et al. (2010). It considered such indicators as population in settlements near the stations, the distance of the observational grounds from the city centers, and the ratio of artificial buildings to circular areas with 2-km radius from observational grounds. The 138 reference stations were originally selected from a dense observational network consisting of 2400 stations, and they have been applied in recent studies (Zhang et al. 2010; Ren and Ren 2011; Zhou and Ren 2011; Ren and Zhou 2014). This work was actually completed around 2007, however, and a number of improvements, in particular the reexamination of the artificial building areas surrounding observational grounds for more than half of the reference stations and an upgrading of the reference network, have been conducted since then.

This paper describes in some detail the assumptions and the steps of this comprehensive method for selecting reference SAT stations in mainland China, including the major improvements and the updated reference SAT network, as well as the latest evaluating results of urbanization effects on the SAT trends found at stations in the national Reference Climate Network and Basic Meteorological Network (RCN and BMN, respectively, or national stations) over the past half a century.

2. The current state of observations

Mainland China has a ground-based climate observational system known for its relatively high-density coverage and longer data records (Li et al. 2004a; Zhang and Xu 2008). The system, operated by the China Meteorological Administration (CMA), includes the Global Climate Observation System (GCOS) Surface Network (GSN; 33 stations), the national RCN (143 stations), the national BMN (682 stations), and the national Ordinary Meteorological Network (OMN, 1592 stations) (Fig. 1). The 33 GSN stations are a subset of the 143 RCN stations, and

TABLE 1. Different historical climate observational networks in mainland China. Urban stations are sited near a settlement with population ≥ 100 000, large city stations are sited near a settlement with population ≥ 1 000 000, and nonurban station are sited near a settlement with population < 100 000.

		GSN	RCN	BMN	RCN+ BMN	OMN	ASN
No. stations		33	143	682	825	1592	2417
Avg population (1000s)		754	199	162	168	84	112
Urban stations	No.	11	39	184	223	306	529
	%	34	27	27	27	18	22
Large city stations	No.	9	6	20	26	9	35
	%	27	4	3	3	1	1
Nonurban stations	No.	13	98	478	576	1344	1920
	%	39	69	70	70	81	77

the RCN, the BMN, and the OMN are independent from each other. The RCN and the BMN are often merged to form a new network (825 stations), which has previously been called the national stations (Ren et al. 2008; Zhang and Xu 2008; Ren and Zhou 2014), but hereinafter is simply referred to as RCN+BMN. Thus, the number of the stations (ASN) with a long enough record of observations is 2417 in mainland China (Fig. 1). Table 1 gives information about the numbers of stations, average population sizes, and numbers of urban and large city stations within the observational networks. Urban stations are defined as those with populations of more than 100 000 in the nearby settlements, and large city stations as those with population more than 1 000 000 in the nearby settlements.

Monthly and daily SAT datasets from the RCN or its variants have been regularly submitted to the World Data Center for Meteorology in Asheville, North Carolina, and have made up subsets of the Global Historical Climatology Network (GHCN) monthly and daily datasets. The GHCN temperature data are the basis of other global land SAT datasets as well, including the CRUTEM, HadCRUT, and NASA GISTEMP products, which have been widely applied in global and regional climate change studies (Karl et al. 1995; Hansen et al. 1999, 2001; Jones and Moberg 2003; Smith and Reynolds 2005; Brohan et al. 2006; Solomon et al. 2007; Stocker et al. 2013). SAT data from RCN+BMN were adjusted for inhomogeneities (Li et al. 2004a; Xu et al. 2013) and have been used extensively by Chinese scientists.

Using the observational data from the RCN and RCN+BMN, researchers conducted many studies of local and regional climate change. The previous studies showed that annual and seasonal mean SATs in mainland China increased significantly, and the overall trends in the past 100 yr are broadly consistent to those of the Northern Hemisphere and the globe as a whole, with the last half a century registering a more significant warming in the country than in the Northern Hemisphere (Wang et al. 1998; Zeng et al. 2001; Qian and Zhu 2001; Hu et al. 2003; Ren et al. 2005, 2012). For the last decade, the data-processing procedures have been improved continuously, aided by the increasing application of inhomogeneity-adjusted data and more sophisticated statistical techniques (Yan et al. 2001; Li et al. 2004a; Ren et al. 2005), but the above conclusions concerning SAT changes across mainland China hold unchanged (Ren et al. 2005, 2012; Ding et al. 2007).

In the meantime, great efforts were made to investigate the magnitudes of urbanization biases in SAT series in mainland China (Y. Ren et al. 2010). Studies found that, with the unprecedented urbanization in the country over the past decades, the SAT trends at the urban and RCN+BMN stations had been significantly affected by the increasing UHI effects (Portman 1993; Yu and Luo 1995; Zhou et al. 2004; Chu and Ren 2005; Zhang and Ren 2005; Chen et al. 2005; Zhou and Ren 2005; Ren et al. 2005, 2007, 2008; Zhang et al. 2005; Yang et al. 2011; Wang and Ge 2012; Li et al. 2013), calling for a further effort to carefully evaluate and correct the urban biases in SAT data series for use in studies of climate change. In north China, for example, stations near large cities registered an annual mean urban warming of 0.16°C $(10\,\mathrm{yr})^{-1}$ on the whole during 1961–2000, accounting for at least 47.1% of the overall warming; similarly, the RCN+BMN stations recorded an annual mean urban warming of 0.11°C $(10\,\mathrm{yr})^{-1}$ on the whole during the same period, accounting for at least 37.9% of the overall warming observed (Zhou and Ren 2005; Ren et al. 2008).

The reasons for the large urbanization effects are not difficult to understand. Because of the historical and unique socioeconomic conditions, the RCN+BMN stations were mostly sited in urban areas or along their fringes (Ren et al. 2008). During the past half a century, however, mainland China has experienced an unprecedented urbanization process. In 1949, the urbanization rate in China was 11%, with a total urban population of only 0.54 billion, but by 2012 those numbers had reached 52.6% and 1.35 billion (Table 2) (Ru et al. 2012, 1–11; Zhuo 2013). A more rapid increase can be seen for built-up areas than for population in the cities and towns of the country over the last decade (Table 2). As cities expanded, especially after 1978 when the reform and openness-to-the-outside policy was initiated, the RCN+BMN stations were gradually engulfed by built-up areas. Under such circumstances, some stations had to be relocated to the nearby suburbs to meet the standards of openness and representativeness set by

TABLE 2. Changes in urbanization rate and built-up areas across mainland China [based on Zhuo (2013) and Ru et al. (2012, 1–11)].

	Year				Annual mean rate of increase since 2002 (%)
	1949	1992	2002	2012	
Urbanization rate (%)	11.0	27.7	39.1	52.6	3.0
Built-up area (km^2)			25973	45565	5.8
Residential area (km^2)			8661	13182	4.8
Road and square area (km^2)			2368	4735	8.0

the CMA. In the eastern plain regions, however, the cities grew so fast that the new locations of the stations were deemed to be less representative of the regional climate again after some years (typically a decade or two), and again they had to be moved farther away from the original locations and the city centers.

Shijiazhuang station was located within a built-up area of Shijiazhuang, the capital city of Hebei Province in the north China plains region, for example, and until 2013 had remained in its original location since its establishment in January 1955 in an outer suburb. By the end of the 1980s and the beginning of the 1990s, the station was now in the built-up areas of the city as the permanent population in the urban areas increased from fewer than 120 000 in 1947 and about 400 000 in 1955 to more than 1 200 000 in 2000. It was one of few stations that had been located within large cities for decades in mainland China, and registered the real urban warming history and large urbanization bias in its mean and extreme SAT series (Bian et al. 2014; Ren et al. 2015). Another example with no relocation but already being engulfed by dense buildings is Bailingmiao station, which lies within a small town with a permanent population of about 23 000 in central Inner Mongolia (Fig. 2). The station was established on 1 December 1953 when the permanent population in the town was only a few thousand. Both Shijiazhuang and Bailingmiao stations are from the BMN and the RCN+BMN, and they have been used for monitoring and studying local and regional climate change.

Most of the RCN+BMN stations, however, have been moved at least once as the observational settings deteriorated and the site representativeness was lowered.

FIG. 2. Locations of the (a),(b) Shijiazhuang (53698) and (c),(d) Bailingmiao (53352) stations. The scales are approximately 1:100 m in (a) and (c) and 1:3000 m in (b) and (d). Yellow points near the centers indicate locations and the observational surroundings of the stations.

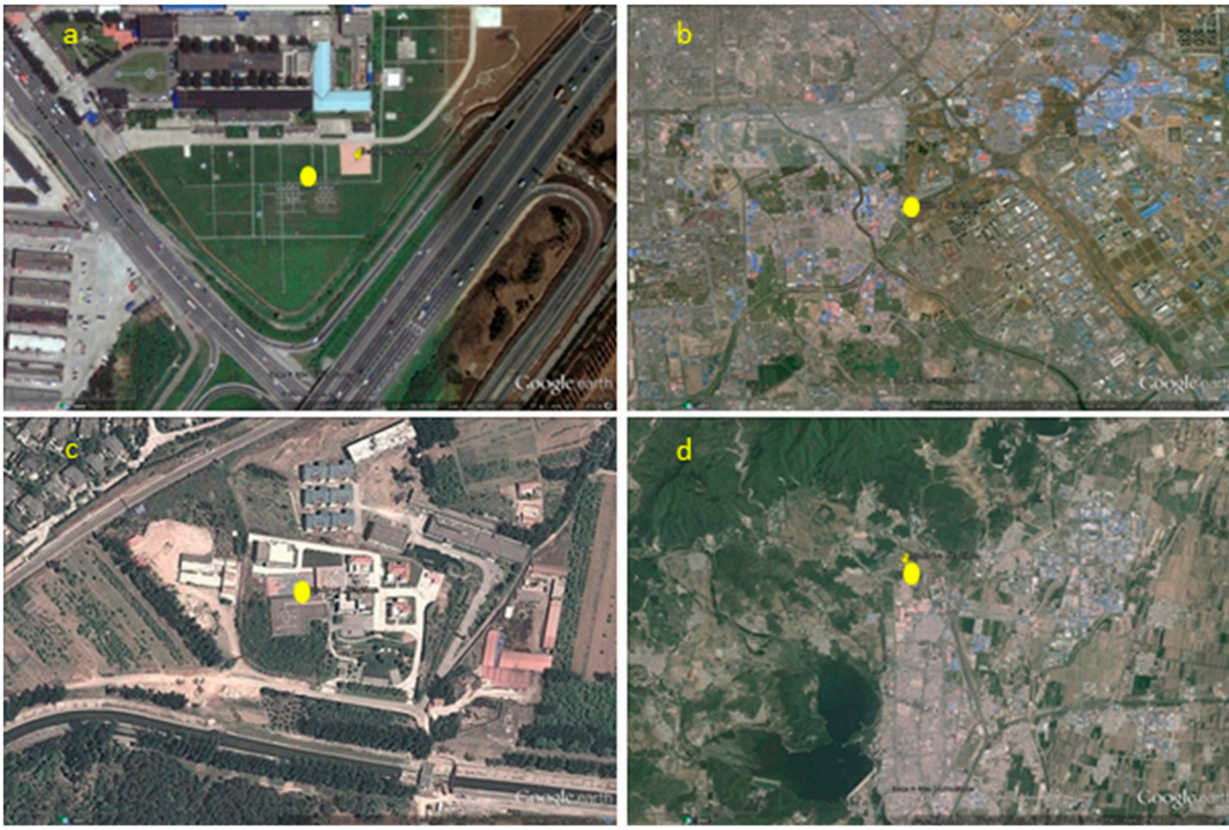

FIG. 3. As in Fig. 2, but (a),(b) Beijing (54511) and (c),(d) Huairou stations (54419).

Beijing station and Huairou station in Beijing experienced relocations, for example, with the former being moved 10 times in the twentieth century and 6 times since 1953 (Zhang and Ren 2014), and the latter station moving twice since its establishment in 1959 (Zhang et al. 2013) (Fig. 3). The last relocation of Beijing station occurred in 1997 when it was moved from a site near the western Third Ring Road to its present location, which is 20 km away. The station has been surrounded by buildings and expressways, however, and has become a typical urban station (Ren and Ren 2011; Zhang et al. 2013; P. Yang et al. 2013).

Figure 4 is a sketch of urban expansion and the relocations of a typical urban station in mainland China. It is probably representative of other developing regions. Perhaps in earlier years, it was located outside the boundary (T1) of the urban built-up area and was less affected by the UHI if it was not in the leeward area of the prevailing wind. A certain time period later, most probably in the 1960s or 1970s in the case of mainland China, the station was engulfed by built-up areas as a result of urbanization and it was well located inside the at-that-time boundary (T2) of the urban built-up area. The station was no longer considered representative according to the standards and requirements of the national meteorological services and it was moved to location L2 in the suburb areas. Location L2 was believed to be a much better site for monitoring the regional baseline weather and climate. Unfortunately, one to two decades later, probably in the 1980s or 1990s in the case of mainland China, the station was once again engulfed

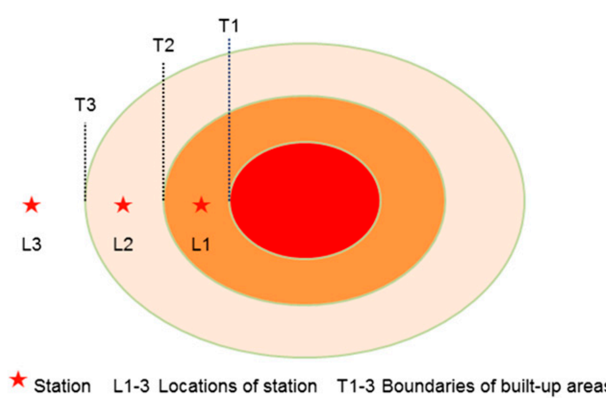

FIG. 4. Sketch detailing the urban expansion and subsequent relocations of a climate station. Boundaries of built-up areas and locations of the climate station for three time periods are displayed.

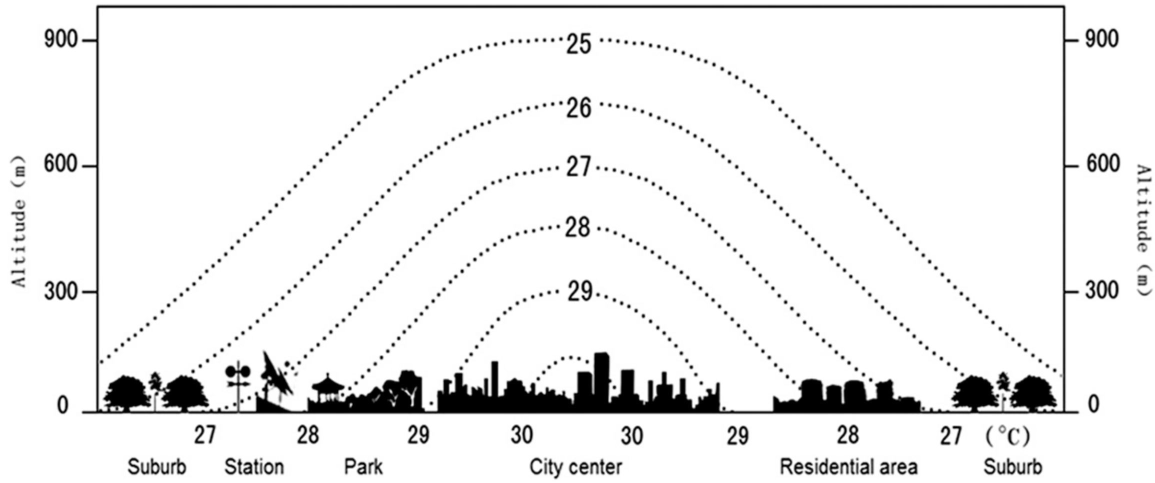

FIG. 5. A sketch of the UHD profile in the boundary layer of an ideal city. [Adapted from G. Ren et al. (2010) with permission of *Meteorological Science and Technology*.]

by built-up areas, and was well inside the boundary T3. In this case, it was forced to move to a new place beyond the L3 perimeter. However, this story has obviously not ended because the city will continue to expand.

In general, the UHI effect is inevitably felt more or less by any city stations, either at an urban or suburban site (Oke 1973). This is because, under calm weather conditions, relatively warmer air in the boundary layer covers a city as a hot air dome in three-dimensional space (Xu and Tang 2002; McNider et al. 2012). Figure 5 shows an ideal profile of an urban heat dome (UHD) under calm weather conditions. The boundary between a given isotherm surface of the UHD and the ground surface does not necessarily end exactly at the outside border of the built-up areas. Instead, it most probably extends somewhere to its outskirts or suburban areas (Oke 1982, 2004; G. Ren et al. 2010). It is understandable that, the bigger a city is, the wider the size of the UHD will be, and the larger the area affected by the UHI effect. It is also obvious that the station close to the center of a city will feel a larger UHI effect.

A problem would result when the SAT data were processed as generally practiced. Much attention was given to data inhomogeneities frequently resulting from station relocations before the regional SAT series was established and analyzed. Various approaches were utilized for the detection and adjustment of the data inhomogeneities (e.g., Peterson et al. 1998; Yan et al. 2001; Li et al. 2004b; Ren et al. 2005; Moberg and Jones 2005). Such a treatment would be necessary, as the corrected SAT data for single stations would produce more homogeneous time series and would be more suitable for analyses of climate change. The adjustments for inhomogeneities, however, were generally to remedy the "breakpoints" in the SAT data series arising from relocations, and to rectify the pre-breakpoint data series against those from the present locations. Since the relocations occurred usually from more urban sites to more rural sites for most regions, the adjusted SAT series would, to some extent, recapture the warming trends induced by the UHI effects.

Figure 6 shows a conceptual model in which the relocations and adjustments for inhomogeneities affected the long-term trends of the SAT series. When a station was located in or near urban areas, a relatively higher SAT was recorded as a result of the UHI effect, and the observing environment there was considered to be less representative of the regional climate condition. The station was hence moved to a suburban site, and the SAT would then witness a sudden drop, creating a breakpoint in the data series. The new location would be good for the first decade or two. However, the station site would be forced to "enter" the urban areas again because of the rapid urbanization, and the SAT would rise gradually under the influence of the increased UHI effect. The station was then relocated once more, and the previous process would be repeated. If the breakpoints were adjusted, then the rectified temperature series would regain a warming trend, because this correction recovered the urbanization effect that was ever weakened in its original data series. The phenomenon was pointed out in previous analyses of U.S. SAT data (Hansen et al. 1999). It was also found in studies of SAT change in mainland China using homogenized SAT data (Ren et al. 2005; Zhou and Ren 2005; Zhang et al. 2013; Li et al. 2014).

It is worth noting that the adjustments for inhomogeneous data are generally incomplete partly because of the insufficient metadata, and the UHI-induced

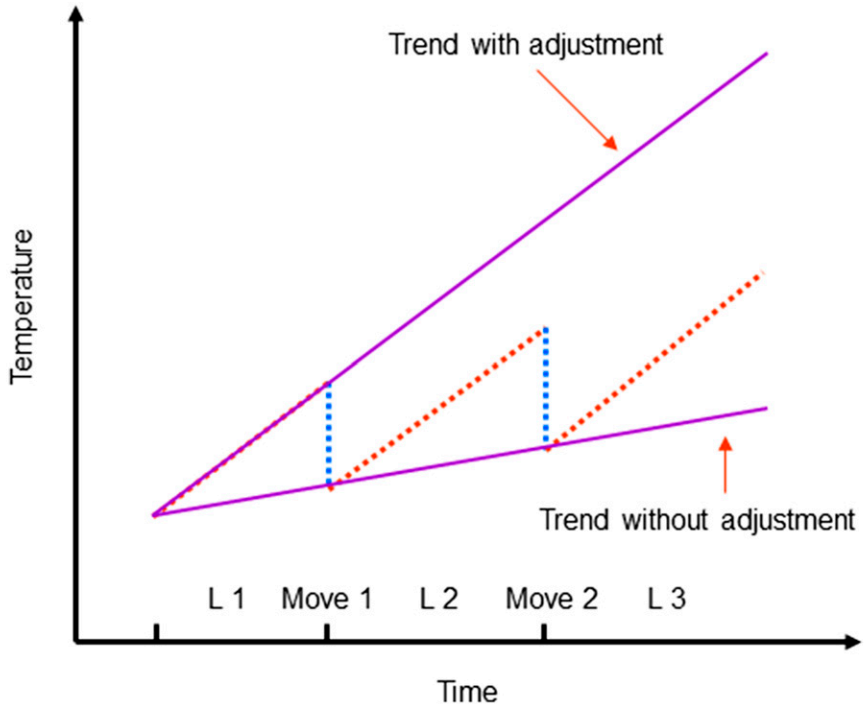

FIG. 6. Effect of station relocation and homogenization on estimates of the surface air temperature trend. [Modified referring to Hansen et al. (1999) and G. Ren et al. (2010).]

warming is thus unlikely to be completely recovered. When the adjustments are made more thorough, however, the increase in urban warming effect will be substantial. For example, the data homogenization for two relocations from downtown to suburbs at Huairou station, Beijing, led to a significant increase in the SAT trend relative to the original data series. The urbanization effects on the annual mean Tmin and Tmax trends were statistically insignificant [$-0.01°C\,(10\,yr)^{-1}$ and $-0.04°C\,(10\,yr)^{-1}$, respectively] for the original data series, but they reached $0.39°C\,(10\,yr)^{-1}$ and $0.10°C\,(10\,yr)^{-1}$, respectively, for the inhomogeneity-adjusted data series (Zhang et al. 2013). A recent comparison of adjusted and original data for Shenyang station, northeast China, once again verified the significantly larger warming trends in the annual mean and minimum mean temperature during the past six decades for the homogenized data at the urban station (Li et al. 2014).

The available historical SAT data from urban stations can broadly be classified into three categories based on the extents to which the homogenization for relocation-induced breakpoints has been done: 1) data with no adjustment made, 2) data with partial adjustment made, and 3) data with complete adjustment made. Obviously, the calculated urban warming using the data with no adjustment would be relatively small, though it would still exist in most cases, and the data with complete adjustment would produce the largest estimate of urban warming trends among all the above categories of data. A notable trend is that climate researchers are being required more than ever to apply the homogeneous data for analyses of climate change, and the SAT data with more complete adjustment are gaining the upper hand, not only in the United States and Europe (e.g., Karl et al. 1995; Easterling et al. 1996; Peterson et al. 1998; Jones and Moberg 2003; Brohan et al. 2006), but also across mainland China and in other regions (e.g., Yan et al. 2001; Li et al. 2004a; Chen et al. 2004; Ren et al. 2005; Nicholls and Collins 2006). This implies that more effort than ever before is needed to reduce the urban biases found when constructing and analyzing the regional or even global land average SAT changes.

Certainly, researchers could choose not to use the SAT data from urban stations for obtaining the regional background temperature trends. Practically, there are indeed two approaches for processing the data: the first is to remove the stations subject to substantive urbanization effects, which is done at the expense of missing longer and more continuous data series, leading to an insufficient number of single-site and regional average temperature series that are long enough, and the second one is to evaluate and adjust the SAT data series contaminated by the urban warming, with the result that such an adjustment is usually far from satisfactory because of the huge difficulty involved with finding truly representative reference stations with comparable lengths of records, as evidenced by previous analyses (Karl et al. 1995; Pielke et al. 2007b; Fall et al. 2010).

Both approaches actually require determining the background climate stations representing a regional temperature change and variability as much as possible. In the first approach, or the non-urban-station approach, the stations affected by the UHI effects are to be eliminated, following certain criteria associated with population, nighttime light intensity, and any other indicators in settlement areas where the stations are located. Experience shows, however, that in order to get a sufficient number of reference stations with data series long enough for use in studies, many urban stations still have to be included. This is especially true for developing regions like mainland China where almost all of the long-term observations are only available from urban stations. Nonurban stations might be more easily chosen in relatively developed regions, but some of them might be still located in towns and might have been significantly affected by urban warming as shown by previous studies (Oke 1973; Karl et al. 1988, 1995; Fujibe 2009; Yang et al. 2011). It is therefore less feasible to apply the first approach. The second approach would be the only option for studies into land surface climate change, in spite of the fact that there are also difficulties in selecting reference stations with relatively longer records for identifying and adjusting the urban biases.

3. Principles, criteria, and procedures

a. Principles

Data from the RCN and the RCN+BMN have been most frequently applied in studies of climate change. However, 31% of the RCN stations and 30% of the RCN+BMN stations are located in/near cities (Table 1), and most of the remaining stations are located in towns (populations between 10 000 and 100 000). It is extremely difficult to get reference stations that are large enough in number from the two networks for evaluating the urbanization effects on SAT data. On the other hand, the number of the OMN stations is more than twice as high as that of the RCN+BMN stations, and the density of the OMN stations is even higher in eastern China, which enables us to find more rural observational sites. Application of the OMN or the ASN is therefore crucial to ensuring representativeness, sufficiency, and the even distribution of the reference stations selected (Ren et al. 2008; Zhang et al. 2010).

In selecting the GSN, principles and requirements were formulated that include the length of station record, data homogeneity, availability of temperature data, future accessibility of the data, and avoidance of urbanization effects (Peterson et al. 1997). It was indeed a very hard task because all of the requirements could be met in only a few regions, and the result of compromising would be that the GSN stations are much more likely to be chosen from those near big cities (Table 1). A main reason for the urban stations to have been included in the GSN was the scoring system used, which assigned too-large weights to the indicators other than the urbanization effect. Considering the importance of the urbanization effect, it is necessary to discard a station if it is found to be located in or near a large city.

We put forward and adopted the following principles, which we feel can be taken as a guide for formulating the specific criteria and procedures for selecting reference surface temperature stations.

1) Sufficient length and good continuity of the observations: Data series should be long enough with good temporal continuity. Continuous and long-time data records from reference stations were a prerequisite for evaluating the urban bias of the target stations. In ideal cases, the time length of observations for reference stations should be fully consistent with that of target stations. If a target station had an 80-yr record, for example, data series of its reference stations had to reach the same record length. However, a large portion of the reference stations in mainland China were to be selected from the OMN stations, most of which were set up in the 1960s or even later, and thus it was difficult to get qualified reference stations that matched the time length of the target stations. As evaluations of urbanization effects were made on the national or regional scale, it was necessary to set a unified beginning time for the reference stations.
2) Stability and immobility of observational sites: Reference stations should be less frequently relocated, and the data inhomogeneities due to the relocations should be clearly documented and adjustable. Station relocations were responsible for most of the identified inhomogeneities of SAT data in some regions like mainland China (Li et al. 2004a; Xu et al. 2013). Because of the limitations of current detection techniques and the unavailability of metadata, not every breakpoint could be confidently identified, making it difficult to perform a complete adjustment. Therefore, as candidate reference stations, it was most desirable that they never be relocated.
3) Immunity to the urbanization influences: It was very important, despite sometimes being extremely difficult, to discard all the stations with poor siting and in

or near the populated urban areas (Pielke et al. 2007a; Ren et al. 2008). Effort had to be devoted to select those truly representing large-scale climate change and variability without the influence of local anthropogenic interference. According to this principle, reference stations should be located in such places as countryside, farmlands without irrigation, grasslands, forests, mountaintops, and nature reserves. There were only a few stations that could meet this requirement, and most of them were found in the mountainous regions of central and western China. There was a big gap between reality and expectation. What could be done was to select ideal stations as much as possible from the existing observational networks. Therefore, some reference stations would inevitably be located near villages or even towns in the eastern plains. As shown in previous studies, the larger the settlements were, the more possible it was that significant urbanization effects on SAT trends would be registered. Although the town stations might be still affected by urbanization, the overall urban warming would be small relative to that for the stations near cities (Karl et al. 1988; Zhao 1991; Zhou and Ren 2005).

4) Sufficiency of stations and uniformity of spatial distribution: A sufficient number of reference stations with a relatively even spatial distribution should be guaranteed. Although SAT change and variability often had better spatial persistency, they might be differently affected by the regional factors such as aerosols and land cover change on a scale beyond cities. To capture the signals of the regional variations, the selected reference stations should reach a certain number, and should be relatively even in spatial distribution. In practice, it was sometimes hard to select a desired reference station in a particular area, and the criteria had to be compromised if necessary. In the plains region of eastern China, for example, many villages and towns where stations were located had eventually grown into small cities, and few stations could be found in truly rural areas. In these cases, the local population, economic level, and specific locations of the stations relative to the built-up areas should be considered.
5) Representativeness of various physical and human environments: This was closely related to the above principle. When the density and spatial distribution of the reference stations met the requirements, various large-scale natural and human environments could be well represented. Differing from the SAT climatological characteristics, the spatial variations in SAT trends were unnecessarily large in such regions as mountainous areas and coastal zones that are climatologically characterized by large horizontal temperature gradients. For climate change studies, therefore, the required density of reference stations in these regions was not necessarily larger than that in other regions.

b. *Criteria and procedures*

The basic information of the 2417 stations in mainland China had been compiled for selecting the reference SAT stations. The information, including station names and codes, latitudes/longitudes, elevations, length of records, missing records, and time of relocations, was mostly available from the CMA's National Meteorological Information Center (NMIC). The population data for the settlements where stations were located were obtained from the year-2000 census report published by the Statistics Bureau of China. Other information, including the size of built-up areas in the settlements where stations were located, the proportion of built-up areas within 12-km^2 circular areas around the stations, and the direct distance of the stations from the centers of settlements, was obtained from Google Earth images and large-scale maps.

Based on the general principles described above, the following specific steps and criteria were set for selecting reference stations.

1) All candidate reference stations had SAT records of over 50 yr, with the beginning of the period of record being no later than 1961. Additionally, the continuity of the temperature data from a reference station was also crucial, and therefore a candidate station was required to have monthly mean SAT data without any missing records. In all, 1330 stations from the ASN network met the two criteria, accounting for about 55% of the total number of stations.
2) The permanent population in the settlements where the stations were located was less than 20 000 in 2000. Such settlements were called villages (population less than 10 000) and towns (population between 10 000 and 100 000), respectively, in mainland China. Out of the 1330 candidate stations, only 260 met this requirement, and they were mostly in central and western China, with far fewer stations in eastern China. Especially in the eastern plain regions where economies were relatively more developed, the stations with permanent populations of less than 20 000 were very limited. To be realistic, therefore, the population criterion had to be compromised for 16 densely populated provinces (municipalities) in the eastern plains and southeastern coastal zones, allowing the permanent population in the settlements where stations are located to be less than 70 000. By this compromised criterion, an additional

72 stations with the nearby settlements having a permanent population between 20 000 and 70 000 could be selected. Considering the permanent population of the nearby settlements, therefore, 332 stations remained on the list of candidate stations.

3) Station relocations had been responsible for most of the data inhomogeneities identified in mainland China, and they had to be taken into account. During the past 50 yr, however, the number of the stations with no movement accounted for less than 33% of the total number of RCN+BMN stations, and less than 35% of the OMN stations. If choices were merely made from these unmoved stations, the number of qualified candidates would shrink sharply. In this case, those stations with the fewest relocations and relatively complete metadata could be considered. It was determined that the number of relocations should be no more than two after 1961, and the horizontal distances for the moves should be less than 5 km in plains and plateau regions. In a few of the eastern plain provinces of Hebei, Shanxi, Hubei, Jilin, Heilongjiang, Jiangsu, Hunan, and Zhejiang, and the western station-sparse regions including western Tibet and southern Xinjiang, the limits for relocation frequency and distance had occasionally been lowered as appropriate for the sake of uniformity in the spatial distribution. During this stage, for those adjacent stations at a distance of around 1° of latitude and longitude, a comprehensive judgment was made to select the best option based on the population of the settlements, descriptions of station locations, times of relocations, and local economic growth rate, in order to ensure the relatively even spatial layout of the selected stations. After this round of screening, 245 stations were left.

4) The settlement populations could not be regarded as a direct indicator of urbanization effects on SAT trends. For the stations exactly within the built-up areas of towns, the urban warming or the UHI effect as registered in the SAT series would be still evident. Therefore, attention had to be also given to the effects of local environmental change around the stations. In the 245 candidate stations, further consideration was made for the very local effect. The surrounding environment of each of the candidate stations was examined with Google Earth images and large-scale maps. The Google Earth images differed in spatial resolution. Some showed considerable detail, enabling the identification of nearby buildings and even the instrument shelters at the observation grounds, while others simply gave rough station positions relative to the built-up areas of the towns. However, more large-scale and clearer Google Earth images became available with time. A circular scope with the station as its center was considered, and the relative proportion or percentage of the built-up area within the scope was measured. The size of the circular scope was set as 12 km^2, or its radius was set at about 2 km. It was determined that the built-up area must not exceed one-third or about 33% of the total, with exceptions of only three stations in data-sparse regions for which the criterion was compromised to less than 40% where the nearby buildings are relatively sparse. Examples from Tuotuohe station, Qinghai Province, and Nehe station in Heilongjiang Province are shown in Fig. 7. Both stations were operated in nonurban areas, with the former owning a permanent population of only 18 000 and the latter a population of about 70 000. Tuotuohe station was located in a small village of the same name along the Qinghai–Tibet Road and Railway, and the area with buildings inside the 2-km-radius circular scope accounts for less than 10% (Figs. 7a,b). It could be classified as a reference station according to the criterion. On the other hand, Nehe station was located in the easternmost part of the town, with buildings inside the 2-km-radius circular scope accounting for more than 33% of the total area, and it is heavily surrounded by nearby buildings (Figs. 7c,d). The station thus could not be taken as a reference station. After this round of filtering, only 148 stations remained, which could serve as reference stations representing a background temperature fields.

5) Finally, out of these 148 stations, 60 were chosen at random for validation of their representativeness by local professionals with independent data and information. This process mainly considered the population of the settlements and the proportions of the built-up areas in 12-km^2 circular scopes around stations and the specific locations of the observational grounds relative to the centers of the settlements. The results showed that more than 80% of those stations well met the requirements. However, the results differed from those obtained by using Google Earth images and large-scale maps for a few sites, though the differences were small. The major reason for the differences might be related to the coarse resolution of the Google Earth images for most of the candidate stations used in 2006. This situation has been improved since then, and an update has been performed, as illustrated below.

After the validation, 5 stations were discarded from the 148-station list mainly because of the excesses of the limit for the proportion of the built-up areas within the 12-km^2 scopes for the eastern areas, and also because of the high

FIG. 7. Distributions of built-up areas inside the 2-km-radius circular scope at (a),(b) Tuotuohe station, Qinghai Province, and (c),(d) Nehe station, Heilongjiang Province, as seen in the Google Earth pictures. The scales are approximately 1:100 m for (a) and (c) and 1:3000 m for (b) and (d). Yellow points indicate locations of the observational stations, and red lines in (b) and (d) denote the 2-km radius from the observational stations located at the centers of the yellow circles.

station density in the central and western areas. The remaining 143 stations from the fifth round of the screening were taken as the final reference stations during the early version of this work (G. Ren et al. 2010; Zhang et al. 2010).

Figure 8 shows the distribution of the 143 reference stations (black and red points). They were relatively sparser in central and northern northeast China, the northeastern China plains, the Taklamakan Desert, and the western parts of the Qinghai–Tibetan Plateau. There were relatively fewer stations in the eastern plains where the economy grew faster and the urbanization level was higher. Overall, the stations were relatively evenly distributed in most regions, and they well represented all natural climate zones and administrative regions. The permanent populations of the settlements near these stations were all below 70 000, below 20 000 for 76% of the stations, and below 50 000 for 96% of the stations.

Recently, an improvement was made for the earlier version of the reference station network. The work was necessary because urbanization occurred so fast that over the past few years a number of the original reference stations were now near built-up areas of the towns and no longer qualified. This improvement was made possible by the available metadata, including high-resolution Google Earth images for more candidate reference stations and photographs of the observational grounds and the nearby microenvironment for some of the candidate reference stations.

Based on the updated information, 13 stations in the original reference dataset were found to be unqualified, mainly as a result of the increased proportions of the built-up areas within the 12-km^2 scopes around the observational grounds. This happened because the towns underwent fast urbanization and the observational sites were too close to the built-up areas of the settlements. The 13 stations are therefore discarded from the reference station list (red points in Fig. 8). At the same time, 13 additional stations were added to the list of reference stations; most of which were from the remainder of the 245 candidate stations as obtained in step 3 above (green

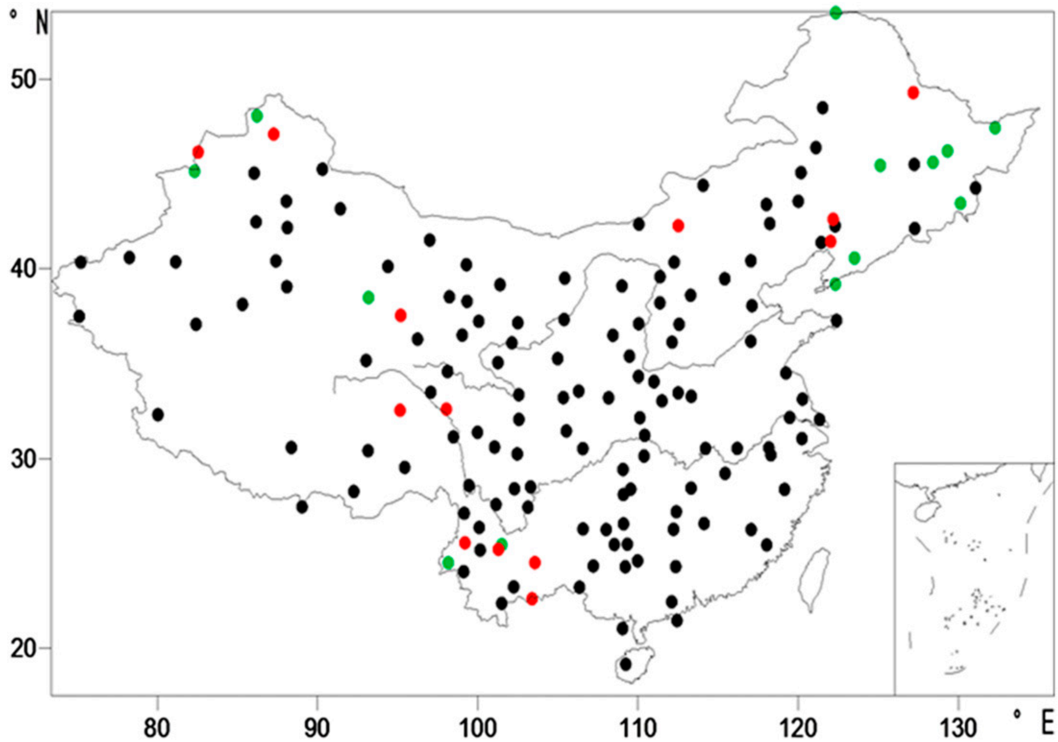

FIG. 8. Distributions of reference surface air temperature stations in mainland China. Black shows original reference stations as they were in G. Ren et al. (2010), red shows the original reference stations that were discarded, and green shows newly added reference stations.

points in Fig. 8). Among them, six were in northeast China where the original reference stations were too sparse, and the other seven stations were chosen to replenish the discarded observational sites. The permanent population in the settlements where the stations were located was compromised on to be less than 100 000 for the newly selected six stations in northeast China, but the other criteria for selecting reference stations remained unchanged.

Most of the selected reference stations in eastern China were located in/near towns with permanent populations between 10 000 and 70 000. As other criteria were taken into consideration, however, the relatively good settings around the observational grounds of the stations had been guaranteed. Figure 9 shows an example from Donggang station, Jilin Province. Donggang was a small town with permanent population 12 000 in the eastern mountains of the province. As an RCN station, it was situated in the northern part of the town, far from the tallest buildings, and it had not been moved since its establishment on 1 November 1956. The angles of elevation of obstacles around the observation grounds at the station were small, and those for the surrounding buildings were all smaller than 5°, showing that a good observational environment had been maintained (Fig. 9).

Thus, an updated reference network with 143 stations had been formed. The number of stations changed accounted for 9% of the total number of original stations. In the new dataset, 70 stations were from the RCN+BMN stations and 73 from the OMN stations. The black and green points in Fig. 8 show the distribution of the new version of reference station network. Taken from a spatial distribution perspective, significant improvement occurred in northeast China, and a few of the stations occupied the originally data-sparse areas in the central and southern plains across northeast China, but little change occurred in other regions relative to the early version.

4. Application of the reference stations

The improved reference station network was applied to evaluate the urbanization effects on the individual stations and region-averaged SAT series for the RCN+BMN dataset over the past few decades. The reason for examining the dataset lies in the fact that it had been extensively used by researchers in their analyses of regional (e.g., Hu et al. 2003; Chen et al. 2004; Ren et al. 2005, 2012; Choi et al. 2009) and global (e.g., Hansen et al. 2010; Lawrimore et al. 2011; Jones et al. 2012)

FIG. 9. Angles of elevation of obstacles surrounding Donggang station, Jilin Province.

climate change and variability trends for the past decade. The RCN dataset had been more frequently used by the end of the 1990s (e.g., Ding and Dai 1994; Wang et al. 1998). The RCN dataset comprised primarily stations near bigger cities, which would also be significantly affected by urbanization.

The RCN+BMN temperature data during 1951–2004 were inhomogeneity adjusted by NMIC. The inhomogeneities, mostly caused by relocations, had been adjusted to match the latest observational locations (Li et al. 2004a; Ren et al. 2005). We did not update the dataset to the present, considering that there might be large inhomogeneities caused by the relocations during the past few years and the application of the Autonomous Weather Stations after about 2004. Data from the 73 reference stations from the OMN network were not adjusted previously by NMIC, but they had been made for homogenization by NMIC using the same method applied previously for the RCN+BMN data, and the adjusted data were available in 2013. Considering the record length, the missing records, and the inhomogeneity adjustments, 591 RCN+BMN stations were finally chosen. Excluding the 70 reference stations, a dataset of 521 RCN+BMN stations was used for the evaluation of the urbanization effect.

The method of Jones and Moberg (2003) was used for constructing region-averaged SAT series and the procedures of Chu and Ren (2005), Ren et al. (2008), Zhang et al. (2010), and Li et al. (2013) are applied for evaluating the urbanization effect and its contribution. The urbanization effect was defined as the linear trends in SAT of the RCN+BMN caused by the strengthening UHI intensity and/or other local anthropogenic factors, and was obtained by calculating the trend difference of the data series between the target stations and the reference stations during the time period 1961–2004. The urbanization contribution was defined as the proportion of the statistically significant urbanization effect to the overall SAT trend at the target stations. Selection of specific reference stations for each of the urban RCN+BMN stations took into consideration the station numbers, the distances from the target stations, and the similarity of the annual-to-decadal SAT variability with that of the target stations. The average series of the selected reference stations for each of all the target stations or urban stations were constructed. Evaluations of the urbanization effects were made on the basis of the single target stations, and the country-averaged urbanization effects were obtained by grid-area-weighted averaging of all the RCN+BMN stations. A detailed illustration of the methods used to evaluate the urbanization effect and its contribution to individual and bulk stations can be found in Ren et al. (2008), Zhang et al. (2010), and Ren and Zhou (2014).

Figure 10 shows the change in annual mean SAT anomalies from the RCN+BMN data and the reference stations in mainland China over the time period 1961–2004, and also the differences in annual mean SAT anomalies between the target stations and the reference stations, or the annual urbanization effects, over the same period. The annual mean SAT anomaly series of both the RCN+BMN and the reference stations experienced a significant increase, but the upward trend was larger for the former than for the latter, indicating an obvious urbanization effect in the RCN+BMN series. The difference series of annual mean SAT anomalies between the RCN+BMN and reference stations exhibited a statistically significant positive trend over the time period analyzed, with the rate of increase or the urbanization effect reaching 0.074°C $(10\,\mathrm{yr})^{-1}$, and the contribution of the urbanization effect to the overall SAT increase reaching 24.9% (Table 3). The urbanization effect and the contribution were very close to those reported by Zhang et al. (2010) using the earlier version of the reference stations, which were 0.076°C $(10\,\mathrm{yr})^{-1}$ and 27.3%, respectively, and those reported by Ren and

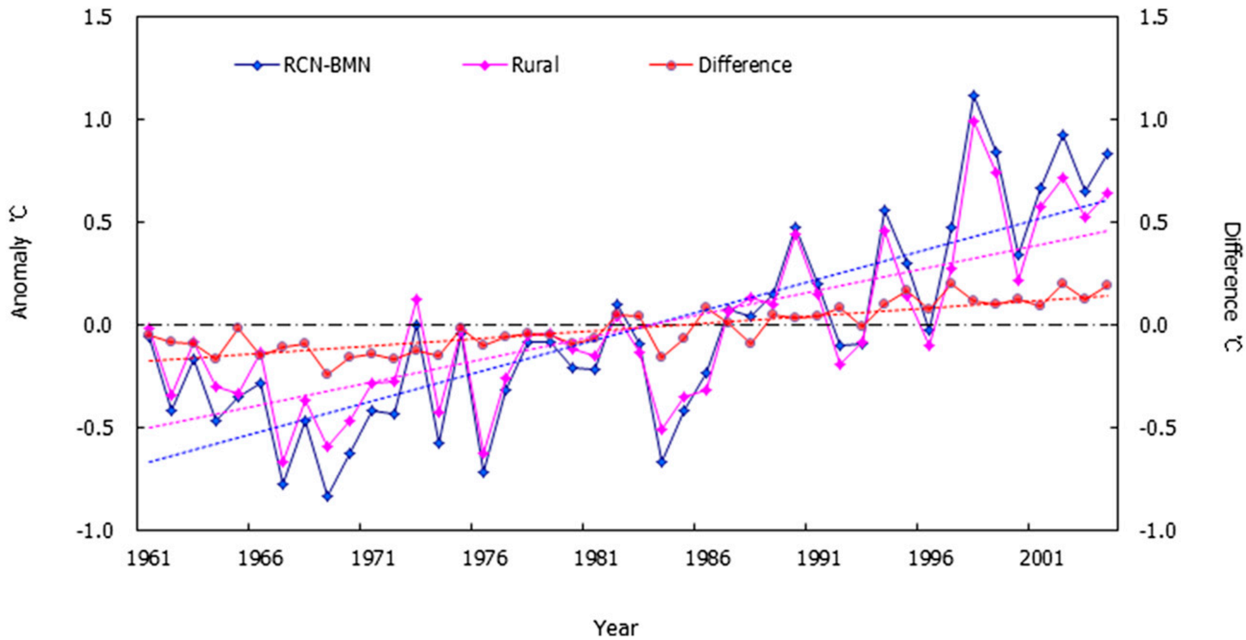

FIG. 10. Annual mean SAT anomalies in RCN+BMN and reference (rural) stations; and their differences across mainland China over the time period 1961– 2004.

Ren (2011) using an independent dataset of reference stations selected by applying satellite data, which were 0.064°C $(10\,\mathrm{yr})^{-1}$ and 23.0%, respectively.

Figure 11 shows spatial distributions of annual mean urbanization effects for the RCN+BMN stations across mainland China over the time period 1961–2004. Significant urbanization effects had been registered for most stations or regions of the country. Only a very limited number of stations witnessed negative urbanization effects, which were generally statistically insignificant. The highly significant positive urbanization effects, mostly ranging from 0.10° to 0.25°C $(10\,\mathrm{yr})^{-1}$, occurred in northern China, central and eastern China, and along the coastal zone, and the significant negative urbanization effects mainly appeared in northwestern China, southern northeast China, and the southwestern part of the country. The spatial pattern of the annual mean urbanization effects was consistent with that obtained by Zhang et al. (2010), as well as with the highly significant urban warming in north China and eastern China, which had been reported by Zhang et al. (2005), Chen et al. (2005), Ren et al. (2008), and Yang et al. (2011).

The country-averaged annual and seasonal mean urbanization effects for the RCN+BMN stations and their significance are given in Table 3. The urbanization effects for the four seasons (spring for March–May, summer for June–August, autumn for September–November, and winter for December–February) were all statistically significant at the 0.05 confidence level, with the largest seasonal mean urbanization effect of about 0.10°C $(10\,\mathrm{yr})^{-1}$ in wintertime, and the smallest one of about 0.05°C $(10\,\mathrm{yr})^{-1}$ in autumn. The seasonal characteristics of urban warming in the RCN+BMN SAT series were thoroughly consistent with those reported for mainland China as a whole in Zhang et al. (2010) by using the earlier version of the reference stations, and were consistent with those given for north China in Ren et al. (2008) by applying an independent dataset of reference stations except for the occurrence of the smallest value during summertime rather than in autumn and a more evenly seasonal distribution of the urbanization effects in north China.

TABLE 3. The country-averaged annual and seasonal mean urbanization effects for the RCN+BMN stations over the time period 1961–2004.

	Annual	Spring	Summer	Autumn	Winter
Urbanization effect [°C $(10\,\mathrm{yr})^{-1}$]	0.074*	0.074*	0.052*	0.049*	0.097*
Urbanization contribution (%)	24.9	29.0	28.7	20.1	20.9

* Statistically significant at the 0.05 confidence level.

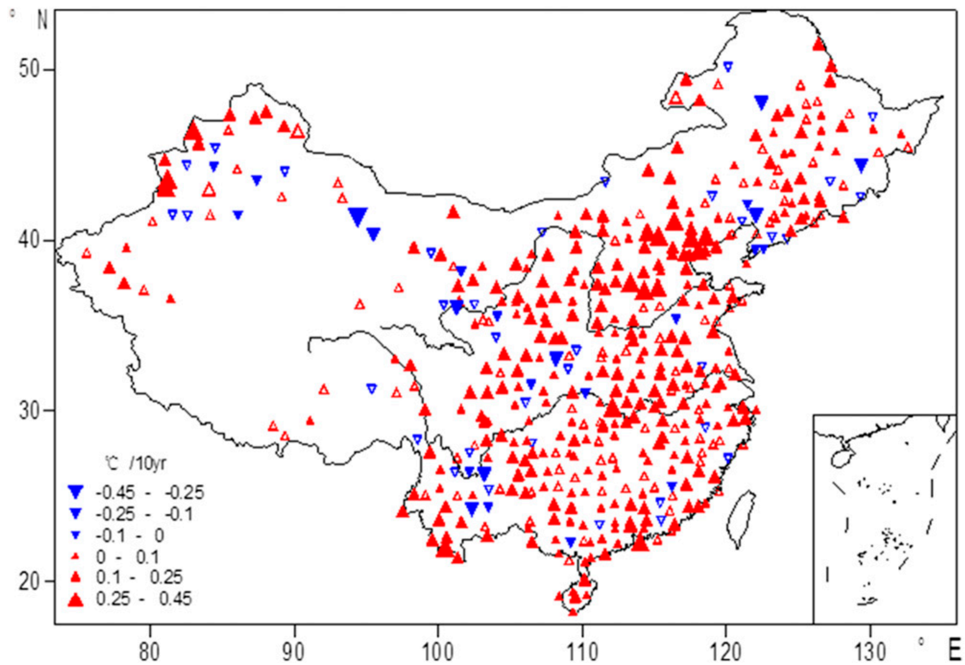

FIG. 11. Spatial distributions of annual mean urbanization effects for the urban RCN+BMN stations in mainland China over the time period 1961–2010. Solid triangles indicate that the urbanization effects are statistically significant at the 99% confidence level.

The temporal and spatial characteristics of the annual and seasonal mean urbanization effects and contributions obtained from this work, therefore, were consistent with our previous works using the data from earlier versions of the reference stations and the data from reference stations selected by applying satellite surface temperature and other indicators (Ren et al. 2005, 2008; Zhang et al. 2010; Ren and Ren 2011; Ren and Zhou 2014). The previous studies also discussed the possible reasons for a few of the distinctive features of the urbanization effects and contributions as confirmed in this paper. For example, the largest urbanization effects and contributions occurred in northern and eastern China over the last half century, which could be related to more rapid urbanization processes in the plains areas of the country (Zhou and Ren 2005; Chen et al. 2005; Ren et al. 2007, 2008; Zhang et al. 2010); larger urbanization effects in winter (summer) minimum (maximum) temperature series, which generally appeared in northern (southern) China over the first half (second half) of the last five decades and which might be related to the combined influences from the earlier (later) popularity of winter centralized heating (summer air conditioning) in the north (south) and other anthropogenic factors (Zhang et al. 2010; Ren and Zhou 2014); and the larger proportion of stations with negative urbanization effects that was found in the arid northwest China region, especially in the northern Xinjiang Autonomous Region during summer, which was mostly likely caused by the oasisization accompanied by the expansion of built-up areas in the cities throughout the desert region (Zhang et al. 2010; Ren and Zhou 2014).

5. Concluding remarks

The trends in surface temperature changes are a key issue for climate change studies. China has a dense observing network, which has long played a major role in meteorological operations and scientific research. However, the network was not designed for climate change monitoring and studies, which require long-term, continuous, homogeneous, and representative SAT records. Frequent relocations and continuous changes in observing settings seriously had affected data homogeneity and representativeness. A fundamental solution would be to create a completely new reference climate network like the U.S. Climatic Reference Network. However, this can hardly meet the demands for the present climate studies.

The ongoing studies predominantly rely on data collected from the existing observing networks. Therefore, it is necessary to identify and select those that can be used for studies on temperature change. We have attempted to develop an integrated procedure for selecting a certain number of reference SAT stations from the existing national meteorological observing network with longer records. With these reference data, the warming bias in SATs from national or urban stations can be systematically evaluated and rectified as appropriate. The reference stations can also be used to analyze the behavior of SAT changes and variability in China over the past few decades.

This paper describes our work and our findings. After defining principles, specific methods and steps are presented, and the 143 reference stations selected are introduced. The long-term SAT data from the reference stations were used as a benchmark to evaluate the urbanization effects in the SAT series of the commonly applied dataset. It was found that the urbanization effects in the annual and seasonal mean SAT series of the national stations across mainland China for the time period 1961–2004 were all statistically significant at the 0.05 confidence level, with the annual mean urbanization effect reaching 0.074°C $(10\,\mathrm{yr})^{-1}$ and the urbanization contribution to the overall warming reaching 24.9%, and with the largest seasonal mean urbanization effect of 0.097°C $(10\,\mathrm{yr})^{-1}$ occurring during wintertime and the smallest one of 0.049°C $(10\,\mathrm{yr})^{-1}$ occurring during autumn. The annual and seasonal mean urban warmings in the RCN+BMN SAT series estimated in this paper were consistent with those previously found when applying independent methods. We were thus confident that the integrated procedure was potentially applicable at national and regional scales, and the SAT data from the updated reference stations network in mainland China could best represent the baseline SAT trends nationwide at present and could be used for evaluating and adjusting the urban biases in the historical data series of the SAT from different observation networks and the varied categories of urban stations. They could also be used directly for monitoring and detecting the regional SAT changes in mainland China.

It should be made clear that the aforementioned reference stations were not truly regional background temperature stations, as they were still subject to local human interference. The principles and criteria formulated for selecting the reference stations had been somewhat compromised for a variety of reasons, and remnant urbanization effects must have been kept in the SAT series of the reference stations. Therefore, the urbanization effects and contributions reported in this paper should be regarded as the lowest estimates.

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