A Remote-Sensing Method of Selecting Reference Stations for Evaluating Urbanization Effect on Surface Air Temperature Trends

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ABSTRACT

In the global lands, the bias of urbanization effects still exits in the surface air temperature series of many city weather stations to a certain extent. Reliable reference climate stations need to be selected for the detection and correction of the local manmade warming bias. The underlying image data of remote sensing retrieval is adopted in this study to obtain the spatial distribution of surface brightness temperature, and the surface air temperature reference stations are determined based on the locations of the weather stations in the remote sensing surface thermal fields. Among the 672 national reference climate stations and national basic weather stations of mainland China, for instance, 113 surface air temperature reference stations are selected for applying this method. Compared with the average surface air temperature series of the reference stations obtained by a more sophisticated method developed in China, this method is proven to be robust and applicable, and can be adopted for the evaluation and adjustment study on the urbanization bias of the currently used air temperature records of surface climate stations in the global lands.

1. Introduction

Detection and attribution of global and regional climate change are mainly based on the instrumental data of the past century in addition to using climate model simulations. Many weather stations that have a long time series of surface air temperature (SAT) records are located near cities and towns, and research has shown that the urbanization of cities and towns has significant influence on the average trends of the SAT at local and regional scales (Magee et al. 1999; Comrie 2000; Kim and Baik 2002; Chu and Ren 2005; Ren et al. 2007, 2008; Zhang et al. 2010). It means that the increasing urban heat island (UHI) might have adversely affected the SAT trends at individual stations and should be corrected before being used for regional and global climate change analysis (Karl et al. 1988; Wang et al. 1990; Portman 1993; Hansen et al. 2001; Ren et al. 2008; Zhou et al. 2004).

Many methods have been adopted for the detection of bias in the SAT records caused by urbanization (Karl et al. 1988; Portman 1993; Hansen et al. 2001; Zhou et al. 2004; Ren et al. 2008). Among them, the most reliable method would be to compare the observation records between the urban and the surrounding countryside stations (Brohan et al. 2006). The urban stations are located in the urban or suburban areas where the SAT observations are influenced by the UHI effect. The countryside stations, or the reference stations, are located far from built-up areas, so the SAT records can represent the baseline climatic conditions. Given that the errors of other human influences can be eliminated, the differences of the SAT trends between the urban and countryside stations are the biases of the urban station SAT series relative to the background temperature change caused by urbanization processes, that is, the influence of urbanization on SAT trends. Therefore, the selection of reference temperature stations is a key point for the study of detection and adjustment of urbanization bias in the SAT series of the city and town stations.

However, different standards and procedures are applied by different research groups to select the reference temperature stations. As a result, obvious differences exist in the reference temperature station networks used in the same region, which becomes the main reason for the inconsistent evaluation results of the biases of the urbanization effect on SAT trends of urban stations or

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any other datasets used regionally or worldwide. For example, Jones et al. (1990) and Li et al. (2004) found an insignificant urbanization effect on SAT trends for China; however, Ren et al. (2008) concluded that the trend of urban warming in north China reaches 0.11°C decade^{-1}, and the contribution of the urbanization effect to total annual mean SAT change as estimated with the national reference climate station (RCS)–basic weather station (BWS) dataset is more than 37.9%. The major cause for the divergence lies in the different methods used to select the reference stations (Ren et al. 2008, 2010). Therefore, the methods for selecting the reference stations are crucial to obtain a reliable analysis result of the urbanization effect on SAT trends of urban stations, which obviously requires further investigations.

In this paper, an objective procedure is developed to identify and determine the reference temperature stations for use in the studies of the urbanization effect on SAT trends. Satellite remote sensing (RS) technology is used to obtain the surface brightness temperature and to draw land surface temperature (LST) isolines surrounding the weather stations. The relative locations of the weather stations in the urban thermal fields can be identified, and then the reference temperature stations can be determined. Owing to the lack of detailed descriptions of the surrounding environments of weather stations and the urbanization processes around the globe, and the RS data advantage in timeliness and uniformity, the method presented in this study has the potential to be used in studies of continental or global scales.

2. Review of previous research

In previous research, various methods have been adopted to classify stations and select the reference stations. A total of five types are summarized below.

a. Nearest observations

It is always adopted in case studies on the urbanization effect of a single urban station. Depending on location, the nearest town-level weather station to a city is selected in this case (Ji et al. 2006; Cheng 2005). For example, Bai et al. (1997) calculate the UHI of the Lanzhou station by comparing the observation data from the Yuzhong, Gaolan, and Baiyin stations, which are all located near small towns. Tian et al. (2006) use the data of four town stations around Xi'an (city) station as a reference series to analyze the UHI of Xi'an station. An alternative procedure is to use lower troposphere temperature (e.g., 850 hPa) from sounding data as a reference series to estimate the weather station UHI magnitude and its change with time (Wu et al. 1994; Ernesto 1997).

b. Classification by population

Depending on population, urban and countryside areas are classified, and then the weather stations located in the countryside areas are selected as reference stations. The population data includes the total population (Jones et al. 1990), urban resident population (Zhou and Ren 2005), and population density (Portman 1993). The population of rural stations is set as less than 0.5 million in eastern China in the study by Jones et al. (1990), but it is set as less than 0.05 million in the study by Easterling et al. (1997).

c. Classification by satellite and map data

The urban stations and reference stations are identified based on data such as the remote sensing nighttime light intensity, true color aerial images, and large-scale maps. Taking the nighttime light for instance, the light intensity of urban built-up areas is usually assumed to be the largest, followed by suburban areas, and then the countryside. Therefore, the light intensity of each pixel in raster images is classified according to three types: the urban area, the suburban area, and the countryside. The weather stations located in the countryside areas are set as the reference stations (Owen et al. 1998; Peterson et al. 1999; Hansen et al. 1999, 2001).

d. Reanalysis data

In recent years, reanalysis temperature data have been adopted as the background field. Comparisons are made between the temperature trends at the surface weather stations and of surface reanalysis temperature series to analyze the effects of urbanization and land use change on the SAT records (Kalnay and Cai 2003; Zhou et al. 2004; Zhang et al. 2005).

e. Classification by mathematical methods

Mathematical methods, such as empirical orthogonal function (EOF) decomposition (Huang et al. 2004; Chu and Ren 2005) and interpolation isotherm (Winkler et al. 1981), are adopted to classify the areas/stations into city-affected areas/stations and countryside areas/stations. For example, EOF analysis is performed on the SAT series of 20 stations in the Beijing region by Chu and Ren (2005), and stations with negative values in the second EOF eigenvector of annual and seasonal mean temperatures are taken as reference stations.

Usually there are fewer weather stations in rural or town-level areas near the city stations, so the nearest observation method tends to be affected by the sufficiency of the selected stations. According to Lowry (1977), the UHI effect still influences suburbs beyond the buildup areas, and the reference stations selected would not be representative. Also, certain differences exist between sounding temperature observations and surface thermometer records, which would not encourage the use of the sounding temperature records as a reference series.

Cities with the same population could be at different urbanization stages due to the differences in the economic development and urbanization processes of countries. Moreover, the inconsistence of statistical methods in countries and regions increases the incomparability of the urbanization levels defined by population. In addition, some indicators are subjective. For example, population totals of 10 000, 50 000, and 100 000 have been used as the indicator to identify country settlements in different studies; however, Karl et al. (1988) found that the urbanization effect can even occur in settlements with a population less than 10 000. Qiao and Qin (1990) also showed that the urbanization effect on surface air temperature records exists at stations near settlements with populations of 10 000–100 000 in China. Therefore, methods using population to classify stations have some limitations when applied to continental- or global-scale studies.

Satellite nighttime light intensity data have been used to identify the land use and land cover changes surrounding stations (Imhoff et al. 1997; Owen et al. 1998; Hansen et al. 2001). Once again, this method has obvious advances over other procedures when used within a country, but it has some problems when used across economic and cultural boundaries. Significant differences of light intensity exist among cities with similar urbanization levels in different countries owing to varied economic development stages, urban expansion patterns, and energy consumption models. Therefore, there is little comparability in different countries and regions that take nighttime light intensity as an indicator for selecting reference stations (Owen et al. 1998).

Problems also exist in the adoption of reanalysis data as background temperature. Most reanalysis products are not of sufficient length for UHI study at present, especially in Europe where urbanization started before 1890. The surface weather station data and reanalysis data have been obtained by different approaches, with the latter being calculated by climate models using observation data that excluded factors such as changes in clouds and surface moisture, which may bias the UHI assessment (Trenberth 2004); therefore, the temperature difference between urban stations and reanalysis data may not be caused only by UHI.

Finally, classification of stations by mathematical methods shows a certain advantage in considering the boundary of urbanization effect. However, for most urban areas, weather station density is not enough for interpolating isotherm, which would lead to a large error of interpolation. Besides, this method does not take into consideration the possible effect of the local buildings around the observation grounds.

Apart from the aforementioned methods, a comprehensive method is used by Ren et al. (2010) to obtain the surface temperature reference station network on the Chinese mainland. In this method, a few indicators—such as settlement population, distance between the station and urban center, and the artificial building area ratio within a radius of 2 km from the station—are adopted, and the multiscale effect of urbanization and the environment surrounding the observation grounds on surface temperature records are also taken into account. However, this kind of method requires large amounts of metadata; thus, it is difficult to apply this method in a semihemispheric or global terrestrial-scale study.

A quite small number of stations can be found to actually represent background temperature change conditions. Because climate change analysis requires a long-enough observation data series, it is more difficult to find suitable observation stations in the countryside or a region not affected by human activity. Under this circumstance, stations have to be selected close to the countryside to represent the baseline climatic conditions to the greatest extent, with which the reference SAT series are generated to evaluate and adjust the urbanization bias existing in the urban station data.

3. Satellite remote sensing method

Due to the UHI, the surface temperature distribution in urban and suburban areas is generally shown as closed isotherms surrounding the urban center. Therefore, theoretically, reference stations can be selected by determining the unaffected area from the UHI effect according to the isotherm distribution with proper isotherm intervals.

Winkler et al. (1981) analyzed the spatial structure of the UHI by mapping the isotherms and then classified stations as rural only if they are located outside of the closed isotherms around the buildup area. However, few weather stations generally exist around most cities of less developed regions. With the insufficient station density, the UHI-affected area is unable to be determined by interpolation of surface temperature records from weather stations. Consequently, it is difficult to adopt this method to select reference stations with the station-observed temperature distribution.

In recent years, opportunities and possibilities have been provided for the selection of surface temperature reference stations by applying remote sensing technology.

Satellite remote sensing is an effective source of information for the study on urban thermal environment, and thermal infrared remote sensing data have been adopted in research on the urban thermal environment by many groups. Gallo et al. (1993, 1999), for example, used the normalized difference vegetation index (NDVI) and surface radiant temperature to explain the temperature difference between rural and urban areas. One of its products is LST, a favorable indicator of the earth's surface energy balance. LST is an effective tool for studying the underlying surface thermal field.

Moderate Resolution Imaging Spectroradiometer (MODIS) data is widely used for its advantages in multispectrum, moderate resolution, and free data sharing (Zhang et al. 2006). He et al. (2005) used the MODIS split-window algorithm to calculate LST and to analyze the urban thermal environment of Guangzhou, China. They found a satisfactory result in terms of the consistency between LST and actual observations. It is therefore feasible to determine the boundaries of UHI-affected areas and to select the rural stations located outside the boundaries by analyzing the spatial distribution of the urban thermal field using MODIS products.

The MOD11A2 8-day LST is chosen in this paper to interpolate the isotherm distribution around weather stations. It is a LST product at 1-km spatial resolution in 0.02 K unit and is the averaged daily LST over eight days. The pixel data are obtained by processing MODIS bands 31 and 32 through the split-window algorithm by the LST team of the National Aeronautics and Space Administration. Elements such as observation angle, water vapor content in atmospheric column, and clouds are taken into consideration in the processing (Wan and Dozier 1996; Wan 2007). The MODIS dataset is available online (ftp://e4ftl01.cr.usgs.gov/MOLT/).

Analysis time is determined to be the seasons or months in which MODIS thermal infrared band detection becomes more sensitive to LST and the retrieval result is more ideal. Data availability is also taken into consideration when determining the time windows. In general, the surface thermal situation is more realistic in winter, and the boundaries of the UHI-affected areas can be identified clearly in mid to high-latitude regions. However, human activity could produce some different effects on the surface thermal situation during the Christmas holidays at the end of December in western countries and the Spring Festival holidays generally occur in mid-to-late January or early February in East Asia (Guo and Ren 2010). Therefore, the average LST from 1 to 8 January 2001 is used in this study to determine the spatial distribution of surface temperature around the stations.

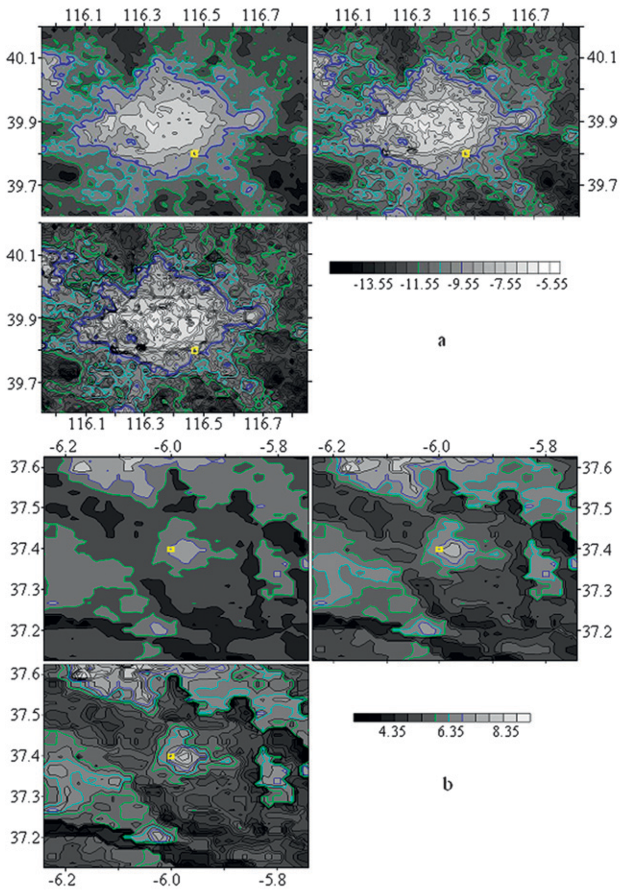
The isothermal interval of LST should reflect the temperature gradient from city centers to suburban belts unaffected by the UHI effect, and it should be less affected by local factors such as microtopography. The isothermal interval chosen should also be proper for maximally saving time and workload.

Experiments are conducted for 10 stations (6 in China and 4 in Europe and central Asia) by adopting various isothermal intervals, including 1.0°, 0.5°, and 0.25°C, so as to determine the most suitable one for classifying stations. The maps of the LST isotherms in the experiments and the following station classifications are all produced using Surfer version 8.0 software in which a kriging interpolating scheme is used.

Figure 1 gives distributions of the different LST isotherms around four stations from the 10 cases. They include Beijing station (No. 54511) and Boketuzhen station (No. 50632) in China, Fichtelberg station (No. 10578) in Germany, and Sevilla station (No. 8392) in Spain. An isothermal interval of 0.25°C can cover more isotherms, but the distribution of the isotherms is more easily affected by microtopography, which interferes with visual judgment. An isothermal interval of 1.0°C is shown to be slightly rough, which makes it difficult to identify the positions of observational grounds in the spatial thermal structure around some small urban stations. An isothermal interval of 0.5°C is a moderate one that can reveal the LST difference between an urban area and the countryside clearly. The isothermal interval of 0.5°C is therefore chosen for mapping the LST thermal fields around the weather stations. It is interesting to note that Winkler et al. (1981) also used 0.5°C as intervals to map the surface air temperature isotherms around cities.

The four aforementioned stations could be taken as examples to illustrate in detail the steps for determining the locations of rural stations. The isotherm distributions are first mapped with LST data around the unclassified station, in this case Beijing (Fig. 1a), Sevilla (Fig. 1b), Fichtelberg (Fig. 1c), and Boketuzhen (Fig. 1d) stations. The maps at isothermal intervals of 0.5°C (the upper right map of each panel in Fig. 1) are then checked to determine the relative locations of the weather stations to the buildup areas or the UHI-affected areas.

Natural and artificial landscape features can be identified using large-scale maps and Google Earth images (Fig. 2). Many natural landscapes, such as volcanoes, lakes, and basins, can also influence the surface thermal structure and sometimes lead to closed isotherms around the stations under investigation. The Google Earth images around the weather stations, for example, can provide valuable information about topography and land cover and they can be used to judge the specific geographical conditions, including the possible influence from large lakes or basins/valleys.



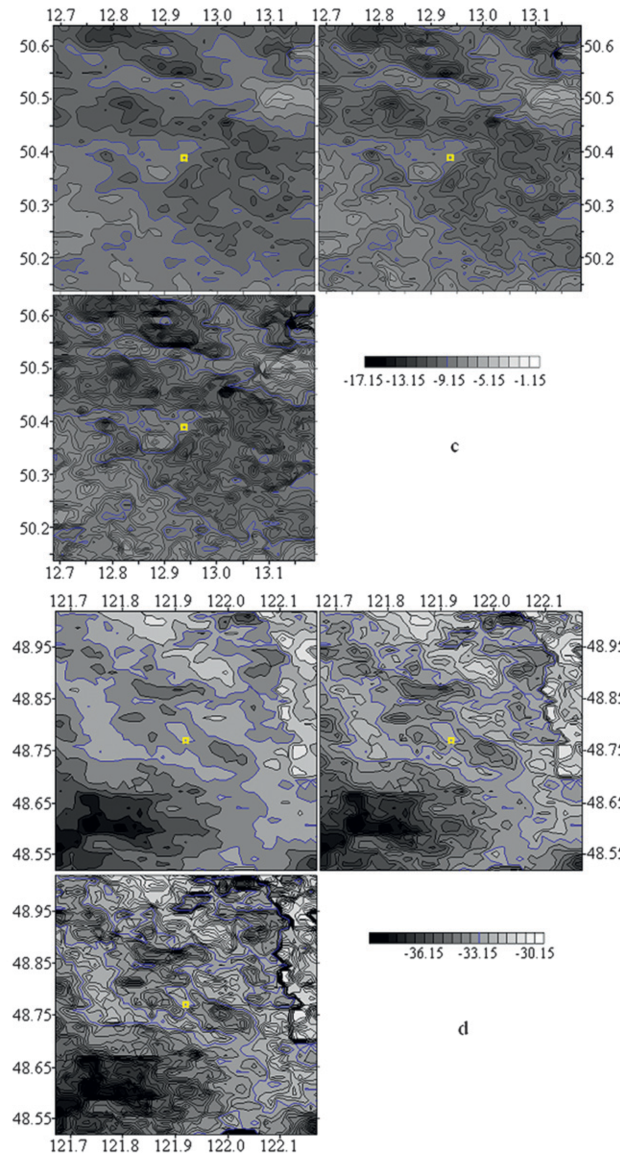


FIG. 1. Average LST isotherm map of (a) Beijing, (b) Sevilla, (c) Fichtelberg, and (d) Boketuzhen stations. The three maps in (a)–(d) show the LST distribution at isothermal intervals of (top left) 1.0°, (top right) 0.5°, and (bottom left) 0.25°C. The small yellow rectangles indicate the station locations.

The Beijing station is located at the urban–rural fringe in the southeastern portion of the city's built-up area and is surrounded by a large number of buildings (Fig. 2a). Figure 1a indicates that the LST of the Beijing region is characterized by an obvious annular distribution from the city center to the surroundings, consistent with the decrease of the UHI magnitude from the built up area toward suburban areas. In addition, the temperature around traffic arteries in outer Beijing is obviously higher than in other areas. Winkler et al. (1981) suggested that the outermost closed isotherm of the annular temperature field in a city or town can represent the boundary of the area affected by the UHI effect. In this case, the outermost isotherm circle is −11.55°C and can be taken as the boundary of the UHI effect in the Beijing city.

It is evident that the Beijing station is located within the −9.55°C isotherm, and the LST difference from the background climatic condition (plain farmland areas) is larger than 2.0°C. Therefore, this station is obviously influenced by the UHI effect and represents the climatic conditions of the urban fringe, so it cannot be selected as a reference station. The large UHI effect on surface air temperature trend at the Beijing station has been reported previously in Ren et al. (2007), with the annual urban warming during 1961–2000 reaching 0.26°C decade^{-1} and its contribution to the overall warming recorded reaching up to 80%.

FIG. 2. Stations and the surrounding landscapes as seen from Google Earth pictures: (a) Beijing (No. 54511), (b) Sevilla (No. 8391), (c) Fichtelberg (No. 10578), and (d) Boketuzhen (No. 50632).

Sevilla station is located in Spain. The outmost circle (5.35°C) of closed isotherms around the station can also represent the boundary of the urban area affected by the UHI effect because, as Fig. 1b shows, the station location near the 6.85°C isotherm is well above the background LST. Figure 2b shows that this weather station is, indeed, located within the built-up area and, therefore, is classified as an urban station.

Fichtelberg station is located in Germany adjacent to the Czech Republic. There is no obvious closed isotherm around the station (Fig. 1c). The settlement area in the southeast portion of the station is quite small, with little population and few buildings near the station. A slight topographical variation can be seen (Fig. 2c), which might have had some influence on the LST distribution. It is clear that Fichtelberg station has not yet been affected by nearby settlement and the UHI effect, and it can therefore be selected as a rural station or reference station.

Finally, Boketuzhen station in China is very similar to Fichtelberg station in Germany in terms of the LST distribution and landscape features (Figs. 1d and 2d) and is also classified as a rural station.

In selecting rural stations, the accuracy of latitude and longitude data, relocation, and the record length of the observations will be taken into consideration and handled properly using the following objectively formulated criteria.

1) The latitude and longitude location data of most stations are rounded to minutes, and errors exist in station locations. Under this circumstance, a station could be located anywhere within a rectangular area $\pm 30''$ from the actual site, as indicated by station location metadata. In equatorial regions, for example, the rectangular areas are approximately 1.86×1.85 km^2. Considering the data errors, the latitude and longitude of the station locations should be

extended by 30″ when analyzing the LST distributions around the stations. Only if the rectangular areas are not influenced by urbanization can the stations be selected as rural stations.

The latitude and longitude coordinates of Beijing station in metadata are 39°48′N, 116°28′E. In MODIS images, the analysis of the LST distributions is conducted for the area from 39°48′30″N, 116°27′30″E to 39°47′30″N, 116°28′30″E. This area is found well within the built-up belt significantly affected by the UHI effect; therefore, the station can be rejected as a rural station.

2) Station moves result in discontinuities of the surface air temperature records and should be treated with caution in the selection of reference stations. Many stations previously located in cities were later moved to suburbs, the countryside, or airports. The urbanization effects will be recovered to some extent with the data homogenization in the temperature series (Hansen et al. 2001; Ren et al. 2010), which will worsen or bias the representation of the station records.

Consideration is given to the historical evolution of station sites. The best candidates for reference stations would be those that experienced no relocation during the operational periods. If relocated stations have to be used, then the times of station moves should be limited to no more than twice and the discontinuities resulting from the moves certifiable and adjustable with the help of metadata. The currently used global land surface air temperature datasets, including those from the NOAA National Climatic Data Center (NCDC), the Met Office Hadley Centre's Climatic Research Unit (CRU), and the NASA Goddard Institute for Space Studies (GISS), have been adjusted for inhomogeneities induced mostly by station relocations, and they can be applied in selecting the reference stations. For mainland China, this study uses the homogeneity-adjusted surface air temperature dataset of the national climate reference stations (CRSs) and basic weather stations (BWSs) (Li et al. 2004).

Generally speaking, urban areas will expand continuously with time. An original countryside or suburb will probably develop into an urban area, but the urban area will generally not be transformed into countryside or suburb. Consequently, the SAT series of the reference stations, selected based on the satellite remote sensing data and with no relocation being documented, will not be affected by the UHI effect at all in the early period and can better represent the background SAT changes throughout the record periods.

3) Long records of the reference stations are required so that they could be taken as benchmarks for evaluating the possible UHI effect on the SAT series for urban stations. Although the requirement can be met for many stations in developed countries, it would be very hard to find a sufficient number of stations with a record length of more than 100 years. In this paper, the starting year of records of reference station records is set to be 1961 for mainland China and other developing countries and 1900 for developed countries.

With the aforementioned methods, we have completed the analyzing and selecting of works for single stations in Northern Hemispheric lands based on the monthly datasets of U.S. NCDC Global Historical Climatology Network (GHCN) and China's RCSs and BWSs. The RCS/BWS datasets consist of 672 stations across mainland China and 113 SAT reference stations, accounting for 16.85% of the total candidate stations, have been obtained this way. The black boxes and green triangles in Fig. 3 show the distribution of the reference stations in mainland China selected with the remote sensing (RS) methods.

The development and urbanization levels of the coastal and plain areas are relatively high, and the candidate stations in the western Tibetan Plateau are very sparse. Therefore, the selected reference stations through the RS method are more densely distributed in central regions. In addition, fewer qualified reference stations are selected in the regions of northeast China, southwestern and southeastern parts of the country, and the coastal zones.

4. Comparisons with other methods

Regional analyses of the urbanization effect on SAT mainly focus on North America and East Asia, including mainland China (e.g., Karl et al. 1988; Karl and Jones 1989; Jones et al. 1990; Zhou et al. 2004; Ren et al. 2008). A series of studies were carried on the urbanization effect on the SAT of East Asia in recent years (Choi et al. 2003; Chung et al. 2004; Ren et al. 2008; Tang et al. 2008; Fujibe 2008). The studies applied different methods for selecting the reference temperature series.

A recent work in mainland China is to adopt all station data—including those of national RCSs and BWSs and almost 1700 ordinary stations and relatively complete metadata—to comprehensively select the SAT reference stations, and then evaluate the temperature change trend observed from the RCS/BWS networks (Ren et al. 2010; Zhang et al. 2010). This method for selecting reference stations is referred to here as the comprehensive method (CM), which considers a number of indicators such as the settlement population near a station, the distance of the observational grounds from

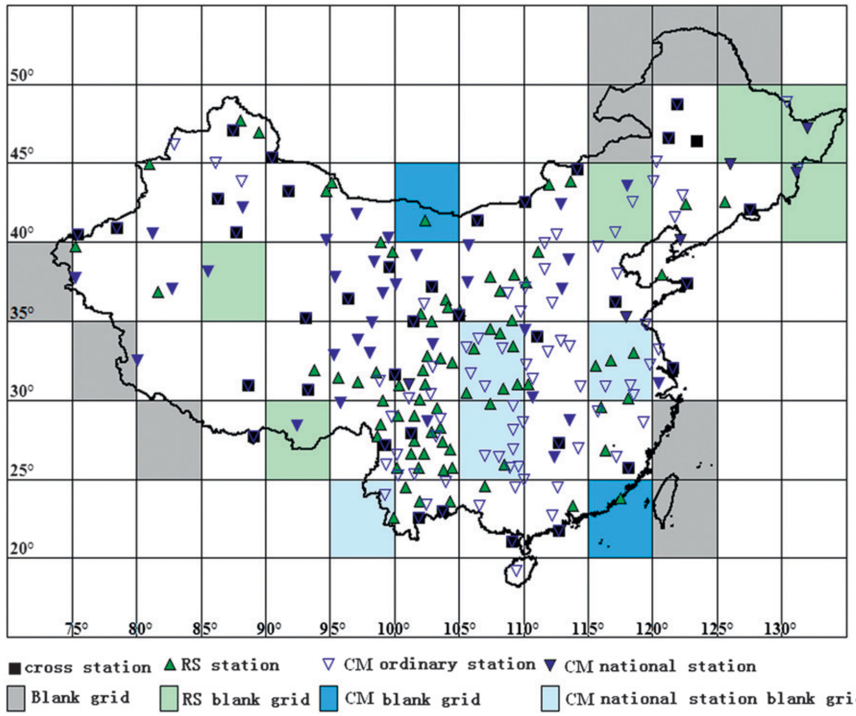


FIG. 3. Distributions of reference stations in mainland China selected with the remote sensing (RS) and comprehensive (CM) methods. Blank grids: no reference station selected with the two methods. Shared stations: the same reference stations selected with the two methods. RS stations: reference stations selected with the RS method. CM ordinary stations: reference stations selected with CM from the ordinary stations. CM national stations: reference stations selected with CM from the national reference climate (RCS) and basic weather (BWS) stations. RS (CM) blank grids: no reference station selected using the RS (CM) method. CM national station blank grids: no reference station selected with CM from the RCS/BWS dataset.

city centers, and the ratio of artificial buildings to total areas within a radius of 2 km from the observational grounds. In addition, this method excludes stations established after 1961 and those with any missing records of monthly-mean temperature. It also discards stations that moved more than twice after 1961.

Finally, 138 reference stations are selected for mainland China, shown in Fig. 3 as black boxes and blue triangles, with open triangles indicating the ordinary stations from a dataset of 1700 stations. The CM reference stations consist of 75 national RCS/BWS and 63 ordinary stations (Table 1). Analysis results using the CM reference stations show that the national average annual urbanization warming in the national RCS/BWS network, or the SAT linear trend difference between the national RCS/BWS and the reference stations or rural stations, is 0.076°C decade^{-1} during 1961–2004, accounting for 27.33% of the overall warming observed (Zhang et al. 2010).

The CM reference station network (Ren et al. 2010) and the corresponding China annual SAT series of the national RCSs and BWSs (Zhang et al. 2010) are adopted here to verify the representation and reliability of the reference station series selected with the RS method. All data have been homogeneity adjusted (Zhang et al. 2010).

Comparisons show that the two methods share 36 stations among the selected reference stations in mainland China (black boxes in Fig. 3), accounting for 26% of those selected with the CM and 32% with the RS method. Twenty-one of the shared stations are located west of 105°E, and the others are mostly distributed in the mountain areas or on islands, where the urbanization effect is relatively small (Fig. 3). Fewer shared stations exist in economically well-developed regions, such as the

TABLE 1. The number of stations selected using different methods in the China meteorological observation networks.

	Number	Shared stations (%)
RS reference stations	113	32
CM reference stations	138	26

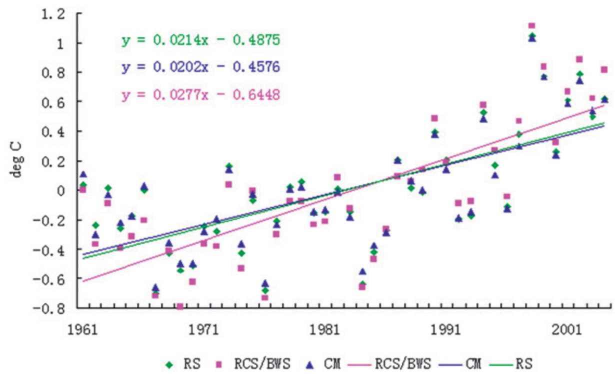


FIG. 4. Annual mean surface air temperature anomalies of the reference stations selected using the RS and CM methods and of the national RCS/BWS network. Straight lines are the linear trends.

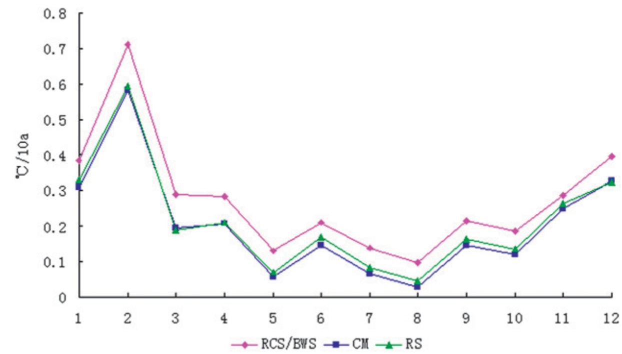


FIG. 5. Monthly mean SAT warming trends at the reference stations selected using the RS and CM methods and at the national RCS/BWS stations.

middle and lower Yangtze basin and coastal regions of the Bohai Sea, where reference stations selected with the CM are usually from the ordinary stations.

Trends of the national average SAT of reference stations from the two methods are compared. Regional average series are constructed with the method proposed by Jones and Hulme (1996), but 2.5° × 2.5° grids are applied for obtaining the grid SAT anomalies. The analysis method of urban warming or urban biases is consistent with that for north China by Ren et al. (2008).

The annual mean SAT series of the two sets of reference station networks are very similar in terms of interannual variability and linear trends (Fig. 4). The linear warming trend is 0.214°C decade^{-1} for the RS method and 0.202°C decade^{-1} for CM, while the national RCS/BWS series registers a 0.278°C decade^{-1} warming. The urbanization effect on the annual mean SAT trends of the national RCS/BWS dataset is 0.064°C decade^{-1} for the RS method, accounting for 23% of the overall warming, and 0.076°C decade^{-1} for CM, accounting for 27% of the overall warming. The urban warming of the national RCS/BWS series and its contribution to the overall warming are well consistent with those given by Zhang et al. (2010). The monthly urban warming trends using the two sets of reference stations therefore show good comparability (Fig. 5).

Among the reference stations selected with the CM method, 46% are from the ordinary stations, which are more likely to be located in the countryside than the national RCS/BWS network, and the reference stations can be selected more easily from the ordinary stations. However, the difference of 0.012°C decade^{-1}, about 4% of the urbanization warming contribution, between the urban warming trends of the two datasets of reference stations can be considered as quite minor (Table 2). This suggests that the RS method for selecting reference stations performs very well and can be used in the evaluation and adjustment of the urbanization effects on SAT time series at climate observational stations for global lands.

5. Conclusions

The selection of reference stations to actually represent the countryside climate is the precondition for the analysis of the urbanization effect on SAT. The current selection methods mostly lack applicability or comparability for large spatial scale. The station classification methods using remote sensing data to select SAT reference stations are discussed in this study. With the selected reference station data from mainland China, the magnitude of the urbanization effect on the SAT series of the RCSs and BWSs, which are frequently used in the regional climate change analyses, is evaluated. The results suggest a high consistency with the previous analysis results using the CM method for selecting reference stations, indicating that the RS method introduced here is applicable to mainland China as well as global lands.

Compared with other approaches to classify climatic stations, the reliance of the RS method on social and economic data is much less, and the updating of data is faster. The RS data is also relatively continuous with higher objectivity and spatial comparability. On continental, hemispheric, and global scales, the RS method

TABLE 2. Comparison of the urban warming for the national RCS/BWS network estimated using the reference stations selected with the RS and CM methods.

	Urban warming for the RCS/BWS network (°C 10 yr^{-1})	Urban warming contribution to the overall warming (%)
RS reference stations	0.064	23
CM reference stations	0.076	27
Difference	0.012	4

has the potential for selecting reference SAT stations, and it could lay a basis for further evaluating and adjusting the urbanization bias of large-scale SAT datasets.

However, the current method could still be improved in the future. In this study, we classify the candidate stations manually one by one using Surfer version 8 to map LST isotherms, referring to Google Earth images. It would be possible to find a way to automatically combine LST data with Google Earth images to determine whether the closed isotherms are affected by urbanization or natural characteristics, such as topography, water, and vegetation. This automatous process would make the RS method for selecting reference stations more objective and more applicable to studies of large-scale lands. In addition, the large-scale contour and biome data could be valuable in differentiating highly variable geographical features in mountainous regions and coastal belts.

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REFERENCES

Bai, H. Z., H. R. Zhang, and C. J. Zhang, 1997: The influences of Lanzhou urban development on local climate. *Plateau Meteor.,* **16,** 410–416.

Brohan, P., J. J. Kennedy, I. Harris, S. F. B. Tett, and P. D. Jones, 2006: Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850. *J. Geophys. Res.,* **111,** D12106, doi:10.1029/2005JD006548.

Cheng, S. L., 2005: Urbanization effect on air temperature change in Lanzhou city for recent 60 years. *Meteor. Mon.,* **31,** 29–34.

Choi, J., U. Chung, and J. I. Yun, 2003: Urban-effect correction to improve accuracy of spatially interpolated temperature estimates in Korea. *J. Appl. Meteor.,* **42,** 1711–1719.

Chu, Z. Y., and G. Y. Ren, 2005: Effect of enhanced urban heat island magnitude on average surface air temperature series in Beijing region. *Acta Meteor. Sin.,* **63,** 534–540.

Chung, U., J. Choi, and J. I. Yun, 2004: Urbanization effect on the observed change in mean monthly temperatures between 1951-1980 and 1971-2000 in Korea. *Climatic Change,* **66,** 127–136.

Comrie, A. C., 2000: Mapping a wind-modified urban heat island in Tucson, Arizona (with comments on integrating research and undergraduate learning). *Bull. Amer. Meteor. Soc.,* **81,** 2417–2431.

Easterling, D. R., B. Horton, and P. D. Jones, 1997: Maximum and minimum temperature trends for the globe. *Science,* **277,** 364–367.

Ernesto, J., 1997: Heat island development in Mexico City. *Atmos. Environ.,* **31,** 3821–3831.

Fujibe, F., 2008: Detection of urban warming in recent temperature trends in Japan. *Int. J. Climatol.,* **29,** 1811–1822.

Gallo, K. P., A. L. McNab, T. R. Karl, J. F. Brown, J. J. Hood, and J. D. Tarpley, 1993: The use of NOAA AVHRR data for assessment of the urban heat island effect. *J. Appl. Meteor.,* **32,** 899–908.

——, T. W. Owen, D. R. Esaterling, and P. F. Jamason, 1999: Temperature trends of the U.S. historical climatology based on satellite-designated land use and land cover. *J. Climate,* **12,** 1344–1348.

Guo, J., and G. Y. Ren, 2010: Climatic effect of the long vacations of "golden weeks" in Beijing-Tianjin-Hebei region. *Meteor. Mon.,* **36,** 114–117.

Hansen, J., R. Ruedy, J. Glascoe, and M. Sato, 1999: GISS analysis of surface temperature change. *J. Geophys. Res.,* **104,** 30 997–31 022.

——, ——, M. Sato, M. Imhoff, W. Lawrence, D. Easterling, T. Peterson, and T. Karl, 2001: A closer look at United States and global surface temperature change. *J. Geophys. Res.,* **106,** 23 947–23 963.

He, Q. J., Z. J. Wu, and Y. W. Zhang, 2005: A study of thermal field in summer of Guangzhou by MODIS thermal infrared data. *Remote Sens. Technol. Appl.,* **20,** 501–505.

Huang, J. Y., X. N. Liu, and Q. X. Li, 2004: The study of relationship between heat island effect and population in cities over south of China. *J. Trop. Meteor.,* **20,** 713–722.

Imhoff, M. L., W. T. Lawrence, D. C. Stutzer, and C. D. Elvidge, 1997: A technique for using composite DMSP/OLS "city lights" satellite data to map urban areas. *Remote Sens. Environ.,* **61,** 361–370.

Ji, C. P., W. D. Liu, and C. Y. Xuan, 2006: Impact of urban growth on the heat island in Beijing. *Chin. J. Geophys.,* **49,** 69–77.

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

——, P. Ya. Groisman, M. Coughlan, N. Plummer, W.-C. Wang, and T. R. Karl, 1990: Assessment of urbanization effects in time series of surface air temperature over land. *Nature,* **347,** 169–172.

Kalnay, E., and M. Cai, 2003: Impact of urbanization and land use change on climate. *Nature,* **423,** 528–531.

Karl, T. R., and P. D. Jones, 1989: Urban bias in area-averaged surface air temperature trends. *Bull. Amer. Meteor. Soc.,* **70,** 265–270.

——, H. F. Diaz, and G. Kukla, 1988: Urbanization: Its detection and effect in the United States climate record. *J. Climatol.,* **1,** 1099–1123.

Kim, Y. H., and J. J. Baik, 2002: Maximum urban heat island intensity in Seoul. *J. Appl. Meteor.,* **41,** 651–659.

Li, Q. X., X. N. Liu, H. Z. Zhang, T. C. Peterson, and D. R. Easterling, 2004: Detecting and adjusting temporal inhomogeneity in Chinese mean surface air temperature data. *Adv. Atmos. Sci.,* **21,** 260–268.

Lowry, W., 1977: Empirical estimation of urban effects on a problem analysis. *J. Appl. Meteor.,* **16,** 129–135.

Magee, N., J. Curtis, and G. Wendler, 1999: The urban heat island effect at Fairbanks, Alaska. *Theor. Appl. Climatol.,* **64,** 39–47.

Owen, T. W., K. P. Gallo, C. D. Elvidge, and K. E. Baugh, 1998: Using DMSP-OLS light frequency data to categorize urban environments associated with US climate observing stations. *Int. J. Remote Sens.,* **19,** 3451–3456.

Peterson, T. C., K. P. Gallo, J. Lawrimore, T. W. Owen, and A. Huang, 1999: Global rural temperature trends. *Geophys. Res. Lett.,* **26,** 329–332.

Portman, D. A., 1993: Identifying and correcting urban bias in regional time series: Surface temperature in China's northern plains. *J. Climate,* **6,** 2298–2308.

Qiao, S. X., and J. Qin, 1990: The diagnoses of the effect from the urbanization of a county town on temperature. *Meteor. Mon.,* **16,** 17–20.

Ren, G. Y., Z. Y. Chu, Z. H. Chen, and Y. Y. Ren, 2007: Implications of temporal change in urban heat island intensity observed at Beijing and Wuhan stations. *Geophys. Res. Lett.,* **34,** L05711, doi:10.1029/2006GL027927.

——, Y. Q. Zhou, Z. Y. Chu, J. X. Zhou, A. Y. Zhan, J. Guo, and X. F. Liu, 2008: Urbanization effects on observed surface air temperature trends in north China. *J. Climate,* **21,** 1333–1348.

——, A. Y. Zhang, Z. Y. Chu, and Y. Y. Ren, 2010: Principles and procedure for selecting reference surface air temperature stations in China. *Meteor. Sci. Technol.,* **38,** 85–98.

Tang, G. L., G. Y. Ren, and J. X. Zhou, 2008: Change of urban heat island intensity and its effect on surface mean air temperature records in southwest China. *J. Appl. Meteor. Sci.,* **19,** 722–730.

Tian, W. W., Z. Y. Huang, and C. J. Hu, 2006: Research on climate warming and urban heat island in Xi'an. *J. Appl. Meteor. Sci.,* **17,** 438–443.

Trenberth, K. E., 2004: Rural land-use change and climate. *Nature,* **427,** 231.

Wan, Z. M., 2007: Collection-5: MODIS land surface temperature products users' guide. ICESS, 30 pp. [Available online at http://g.icess.ucsb.edu/modis/LstUsrGuide/MODIS_LST_products_Users_guide_C5.pdf.]

——, and J. Dozier, 1996: A generalized split-window algorithm for retrieving land-surface temperature from space. *IEEE Trans. Geosci. Remote Sens.,* **34,** 892–905.

Wang, W. C., Z. Zeng, and T. R. Karl, 1990: Urban heat island in China. *J. Geophys. Res. Lett.,* **17,** 2377–2380.

Winkler, J. A., R. H. Skaggs, and D. G. Baker, 1981: Effect of temperature adjustments on the Minneapolis–St. Paul urban heat island. *J. Appl. Meteor.,* **20,** 1295–1300.

Wu, X., S. W. Wang, and D. M. Lu, 1994: The analysis of heating effect of urbanization. *Meteor. Mon.,* **20,** 7–9.

Zhang, A. Y., G. Y. Ren, J. X. Zhou, Z. Y. Chu, Y. Y. Ren, and G. L. Tang, 2010: On the urbanization effect on surface air temperature trends over China. *Acta Meteor. Sin.,* **68,** 957–966.

Zhang, J. Y., W. J. Dong, L. Y. Wu, J. F. Wei, P. Y. Chen, and D. K. Lee, 2005: Impact of land use changes on surface warming in China. *Adv. Atmos. Sci.,* **22,** 343–348.

Zhang, Y. W., Q. J. He, X. L. Zhao, and Y. Q. Wu, 2006: A remote sensing monitoring and analysis of land surface temperature at Pearl River Delta in July 2005. *Meteor. Mon.,* **32,** 23–37.

Zhou, L. M., R. E. Dickinson, Y. H. Tian, J. Y. Fang, Q. X. Li, R. K. Kaufmann, C. J. Tucker, and R. B. Myneni, 2004: Evidence for a significant urbanization effect on climate in China. *Proc. Natl. Acad. Sci. USA,* **101,** 9540–9544.

Zhou, Y. Q., and G. Y. Ren, 2005: Identifying and correcting urban bias for regional surface air temperature series of north China over period of 1961–2000. *Climatic Environ. Res.,* **10,** 743–753.