A Dynamic Method for Quantifying Natural Warming in Urban Areas

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Abstract In the study of global warming, one of the main issues is the quantification of the urbanization effect in climate records. Previous studies have contributed much to removing the impact of urbanization from surface air temperature by carefully selecting reference stations. However, due to the insufficient number of stations free from the influence of urbanization and the different criteria used to select reference stations, there are still significant controversies about the intensity of the impact of urbanization on temperature records. This study proposes a dynamic method for quantifying natural warming using information on urbanization from every station acquired from remote sensing (RS) data instead of selecting reference stations. Two different spatial scales were applied to examine the impact of urbanization, but little difference was found, indicating the stability of this method. The results showed a significant difference in original temperature data and the homogenized data—urban warming accounted for approximately 64% in the original temperature warming but only approximately 20% in the homogenized temperature records.

Keywords: urbanization, air temperature, climate change, remote sensing


1 Introduction

In the study of global warming, one main issue is to quantify the urbanization effect in climate records, as the data acquired by many weather stations are affected by the development of human settlements. Previous research has shown that urbanization has had significant impacts on meteorological records (Landsberg, 1981; Kukla et al., 1986; Karl et al., 1988; Changnon, 1992; Ren et al., 2008). Therefore, to detect global and regional climate change with meteorological data, urban signals must be removed from the original data as the first step.

Appreciable efforts have been made to remove the bias in meteorological records caused by urbanization signals (Ren and Ren, 2011, summarized in Table 1). In these studies, rural stations were carefully selected as reference stations that were assumed to be unaffected by the urbanization process, therefore representing the regional climate (Karl et al., 1988; Portman, 1993; Hansen et al., 2001; Ren et al., 2008). Several rules were adopted to distinguish between urban and rural stations, such as by the distance to city center, based on population or remote sensing data. Observation minus reanalysis (OMR, Kalnay and Cai, 2003) was another important method in estimating the urban effect. Mathematical methods, such as empirical orthogonal function (EOF) decomposition (Huang et al., 2004; Chu and Ren, 2005), were also adopted to distinguish between urban and rural stations.

All the methods mentioned above had their advantages in evaluating the urban effect; however, they all encountered an inevitable problem by assuming that rural stations were free from urban impacts. In fact, only a small number of stations are free from urbanization, and most of these stations are located in mountainous areas, where the circulation and topography are all different from that of the stations on the Beijing plain are more relevant to large-scale climate patterns. Additionally, the criteria used to classify urban or rural stations are static—once a station is categorized as a rural station, it is used to represent the regional climate. However, urbanization is a dynamic process, and its impact on air temperature also differs with time and the intensity of urban expansion.

Considering the importance of identifying urban vs. rural meteorological stations in examining climate warming, this study proposes a dynamic method to examine the contribution of urbanization signals in climate records and to attribute the large-scale climate warming driven by global and regional forcing. Instead of categorizing each station into several groups (e.g., urban, suburban, and rural stations) and therefore losing the valuable urbanization information of each station, this method compares the trends of urbanization and surface air temperature (SAT) over each station to further evaluate urbanization effects on climate records.

2 Methods

Beijing was chosen as the study area to examine urban expansion around meteorological stations and its potential impacts on temperature records due to the rapid urbanization of Beijing during 1978–2008.

To obtain the urbanization rate around each meteorological station, a remote sensing classification was performed with cloud-free Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM) images from 1978–2008 (Table 2). Then, the urbanization rate was calculated by applying the ordinary least squares (OLS) method to each year’s urban areas.

Time series of air temperature data from eight meteorological stations in Beijing and two stations in nearby
Hebei without relocation were collected and processed from 1978 to 2008. We used both original data (SAT) with comprehensive quality controls and homogenized data (Homo-SAT, Li and Yan, 2010). The geographical locations of the 10 stations were accurately positioned on Google Earth. To examine the relationship between temperature data and Land Use/Cover Change (LUCC) at different scales, 8×8-km and 1×1-km subsets around each of the 10 meteorological stations were extracted from the satellite data (Fig. 1).

A 30-yr annual mean (Homo-)SAT linear trend was also calculated with the OLS method. Let \( x_{ij} \) stand for the urbanization rate and \( y_{ij} \) stand for the (Homo-)SAT trend of station \( i \); then, we obtain 10 pairs of \( (x_{ij}, y_{ij}) \) points in a 2-D scatter plot. After the same OLS method was applied to those points, a relationship \( y_{ij} = a x_{ij} + b \) was established, where \( a \) and \( b \) are statistical parameters gained from dataset, and the coefficient of determination \( (R^2) \) represents the quality of the correlation between the urbanization rate \( (x_{ij}) \) and the (Homo-)SAT trend \( (y_{ij}) \) for those stations.

Because there were few stations free from urban expansion in Beijing during 1978–2008, the traditional way to find reference stations lost its effectiveness. Fortunately, because \( x \) represents the urbanization rate in our established formula, when \( x = 0 \), \( y \) represents the regional climate warming free from the urbanization process; this is the key point that differs from previous studies.

### Table 2 Remote sensing data used in this study.

<table>
<thead>
<tr>
<th>Path</th>
<th>Row</th>
<th>Date</th>
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<tbody>
<tr>
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</tr>
<tr>
<td>MSS</td>
<td>133</td>
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<td>133</td>
<td>34 05/03/1979</td>
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<tr>
<td>TM</td>
<td>123</td>
<td>34 09/10/1987</td>
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<tr>
<td>TM</td>
<td>123</td>
<td>33 02/11/1989</td>
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<tr>
<td>TM</td>
<td>123</td>
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<tr>
<td>TM</td>
<td>123</td>
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<tr>
<td>TM</td>
<td>123</td>
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<tr>
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<td>123</td>
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<tr>
<td>TM</td>
<td>123</td>
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<td>TM</td>
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</tr>
<tr>
<td>TM</td>
<td>123</td>
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</tr>
<tr>
<td>TM</td>
<td>123</td>
<td>32 09/27/2007</td>
</tr>
</tbody>
</table>

After the natural climate warming is quantified, the urbanization impact can be easily calculated with one of the following equations:

\[
a \cdot x_{ij} \cdot y_{ij}, \quad (1)
\]

or

\[
1 - b / y_{ij}, \quad (2)
\]

In Eq. (1), the urbanization rate was used to directly evaluate the urban impact on SAT trends over the meteorological station. In Eq. (2), the impact is indirectly expressed as the total warming minus the natural climate change under large-scale forcing.

### 3 Results

#### 3.1 Decadal urban land-use changes derived from Remote Sensing data (RS)

In this study, four classes (built-up, bare soil, green vegetation, and water) were distinguished (Fig. 1). The overall accuracy was 96.8% for TM and 89.8% for MSS, and the Kappa coefficient was 0.92 for TM and 0.85 for MSS. The Producer and User Accuracy values of the urban class for TM were 90.8% and 96.9%, respectively, and 80% and 92.3% for MSS, respectively. The urbanization rate and climate-warming trend of two stations are given in Fig. 2.

During 1978–2008, the stations located in the Beijing plain all experienced rapid urbanization. The predominant land cover in several stations located in central Beijing was converted from natural vegetation to an urban setting. Although the urban areas in nearby Hebei did not expanded as quickly as in Beijing, they were still accompanied by moderate urbanization processes. For the Raoyang and Nangong stations, the built-up areas increased approximately 10% within an 8×8-km² area during 1978–2008. Although these stations are still surrounded by relatively low built-up areas, the impacts of urbanization did exist due to the high urban expansion rates.

#### 3.2 Contribution of natural and urban warming

The relationship between the urbanization rate and the (Homo-)SAT trend was mostly linear at both spatial scales (8 km and 1 km). For the original SAT, the \( R^2 \) was 0.89 for the 8-km patch and 0.79 for the 1-km patch; for Homo-SAT, the \( R^2 \) was 0.77 for the 8-km patch and 0.74 for the 1-km patch (see Fig. 3). Similar patterns were revealed in these analyses—the higher the urbanization rate, the faster the temperature increased.
Figure 1  (A) Locations of 10 Meteorological stations and (a1) MSS/(a2) TM/(b) QuickBird images around Tongzhou station. Red box indicates 8-km range, yellow box indicates 1-km range. (a1) is standard false-color composite MSS image acquired on 20 September 1978, (b1) and (b2) are QuickBird images acquired from Google Earth on 25 April 2006. (a2) is standard false-color composite TM image acquired on 27 September 2007. (a3) is the classification result of (a1); the red color represents the urban area, green represents vegetation, and blue represents water.

Figure 2  The rate of urbanization and climate warming of two unmoved stations.

For the original SAT, the background climate warming was approximately 0.18°C/10-yr within the 8-km and 1-km spatial extents around the meteorological stations. For the Homo-SAT, the natural climate warming was up to 0.45–0.46°C/10-yr within the 8-km and 1-km extents. There were few differences in background climate warming between the spatial extents of 1 km and 8 km, but the differences between the original SAT and Homo-SAT were significant. Moreover, the impacts of urbanization in the 8-km and 1-km clusters were different; with 10% more urban area developed within the 1-km range, the original SAT would likely have increased by 0.21°C, while within the 8-km extent, it would have increased by as much as 0.44°C. For the Homo-SAT, with a 10% greater urban proportion in the 1-km and 8-km extents, the temperature would only increase by 0.055 and 0.11°C.
respectively. The temperature increase in the large cluster (8 km) was only approximately twice that of the small one (1 km); with the same increased proportion of the urban area, the area of the large cluster was 64 times greater than that of the small cluster. The differences in impacts of the urban fraction on climate records between the 8-km and 1-km areas around meteorological stations provide critical information on the spatial scale of such effects. Clearly, areas farther away had a reduced impact on the recorded temperature.

During 1978–2008, the air temperatures recorded by meteorological stations were accompanied by urbanization processes to different degrees due to the speed of the urban expansion around the different stations. The overall urbanization-induced warming accounted for 61.6%–81.4% for the 8-km extent (61.7%–79.0% for the 1-km extent) in the Beijing stations (excluding the mountainous area stations) and for 46.2%–51.8% (49.5%–63.8% for the 1-km extent) in the two Hebei stations (Table 3). The results calculated by the two methods were similar. However, the urbanization impact on Homo-SAT was much less than that on the original SAT, with urban warming accounting for only 9.8%–37.2% and 11.9%–36.4% for the 8-km and 1-km extents in the Beijing stations, respectively. For the two Hebei stations, the urban-related warming was 10.9%–13.1% and 13.0%–19.7% for the 8-km and 1-km extents, respectively.

4 Discussion

4.1 A dynamic approach to quantifying natural warming in urban areas

Our results demonstrate that the SAT trends were likely affected or contaminated by decadal urban expansion around the met stations. The traditional approach to selecting reference/rural stations to represent natural warming only considers the distance of the station to the city center (Ji et al., 2006; Cheng, 2005) or population data (Jones et al., 1990; Portman, 1993; Zhou and Ren, 2005), but rarely accounts for actual land-use changes around stations over the entire study period.

It is critical to separate urban vs. rural stations in a dynamic way to better understand local and regional climate warming without Urban Heat Island (UHI) signals. By the traditional definition of rural stations, Nangong and Rao- yang may be treated as reference stations (warming trend: 0.36°C/10-yr), as their urban area and population were among the lowest. However, the regional climate warming was only 0.18°C/10-yr when adjusting for the urbanization effect in this study. When choosing meteorological stations to summarize regional temperature changes, it is important to fully consider the dynamic land-use around the stations and ensure there was no major urban expansion around the reference stations throughout the study period. Otherwise, it will be inappropriate to interpret
Table 3 Contribution of urban warming in (Homo-)SAT for 8 km and 1 km extents.

<table>
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<tr>
<th></th>
<th>8 km</th>
<th>1 km</th>
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<tr>
<td></td>
<td>1–b/y</td>
<td>ax/y</td>
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<tr>
<td>Mentougou</td>
<td>61.97%</td>
<td>61.24%</td>
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<td>Changping</td>
<td>67.62%</td>
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<td>Fengtai</td>
<td>71.27%</td>
<td>71.16%</td>
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<tr>
<td>Tongzhou</td>
<td>81.85%</td>
<td>80.92%</td>
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<td>Nangong</td>
<td>48.14%</td>
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<td>Raoyang</td>
<td>50.68%</td>
<td>52.93%</td>
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<td>AVG</td>
<td>63.59%</td>
<td>64.33%</td>
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<th></th>
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<th>1 km</th>
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<tbody>
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<td>ax/y</td>
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<td>4.41%</td>
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<td>Nangong</td>
<td>10.92%</td>
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<tr>
<td>AVG</td>
<td>26.29%</td>
<td>15.90%</td>
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</table>

Note: "−" indicates negative number.

UHI-driven local warming as a regional trend.

Although our results suggest that urbanization significantly affected the climate records from meteorological stations, they did not provide evidence of the impacts of urban expansion on the regional climate, as our results only revealed what occurred at the local scale around meteorological stations and how the signals of urbanization contributed to the temperature records.

4.2 Impact of spatial extent of urbanization on the (Homo-)SAT trend

In this study, two scales of urbanization (8×8 km² and 1×1 km²) were selected to examine the impact on the (Homo-)SAT trend. The ranges in the semivariograms of each station were all within 8 km, which may indicate that land use beyond that range had little spatial autocorrelation. Meanwhile, the predominant LUCC was found to have a greater impact on the observed diurnal temperature range (DTR) within the microscale (0.1 km) rather than the mesoscale (10 km) (Gallo et al., 1996). It was also suggested that the source area of heat energy, affected by the wind direction and strength, only contributed at a narrowly local scale in the city area (within 1×1 km², personal communicated with James Voogt, 2011).

As the results indicate, the choice of spatial scale had little influence on the background climate warming and thus on the contribution of the urbanization signal in the records. However, with 10% more urban area, the impact of the 8×8-km² area contributed far less than 64 times that of the 1×1-km² area; in fact, the larger spatial extent only had approximately twice the influence of the smaller extent. This result demonstrates that the larger area had much less influence on the SAT recorded by the meteorological stations, just as former studies demonstrated (see Gallos et al., 1996). In other words, the impact of urban buildup fractions on climate records is mostly limited within a 1-km radius of a meteorological station and is a local phenomenon, although it has global implications if improperly treated to represent regional and global warming trends.

4.3 Differences between SAT and Homo-SAT

The urban-induced warming trends differed significantly between those using the original SAT and Homo-SAT. The urbanization impact on the SAT trend accounted for approximately 64%, while it only accounted for 18.7%–20.7% on the Homo-SAT. Because uncertainties existed in both the original and homogenized data, the reasons for this difference cannot be easily explained.

Even relocation biases were carefully removed from this study, so uncertainties such as instrument changes may still exist in the original SAT. Uncertainties in the Homo-SAT may have been caused by the way the temperature data were homogenized. The method adopted was Multiple Analysis of Series for Homogenization (MASH), which compared surrounding reference stations to reconstruct the temperature of each station (Szentimrey, 1999, Li and Yan, 2010). By homogenization, the results became relatively insensitive to land cover change. Urban warming signals may also be introduced into the mountain stations by comparing them with the nearby plain stations, which were accompanied by significant urban expansion. For example, the average temperature trend of the three mountain stations (XYL, THK, and ZT) was 0.11°C/10-yr for the original data but was up to 0.45°C/10-yr for the homogenized data. Although the homogenized data were comparatively reliable for analyzing large-scale climate trends, they may not be suitable for
investigating the impacts of surrounding land surface change on local-scale climate.

4.4 Attribution of climate warming

In this study, we found that during the past three decades, urban-induced warming contributed 61.6%–81.4% and 9.8%–37.2% to overall warming for the plain stations in Beijing using the original SAT and Homo-SAT, respectively. Some researchers have found that the large UHI effect on the original air temperature trend at the Beijing station reached as high as 80% in the overall warming during 1961–2000 (Ren et al., 2007). It was also found that urbanization contributed to 73.5% of the local warming from 1979 to 2006 in Beijing by comparing observation and reanalysis data, but the contribution of urbanization dropped to only 34.4% when using the traditional rural-urban data comparison approach (Si et al., 2009), which indicates the importance of selecting reference data for regional climate. However, the data may likely misdirect our interpretation of the overall warming trend at the regional scale if this signal is treated improperly.

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References


