Evaluating the contributions of urban surface expansion to regional warming in Shanghai using different methods to calculate the daily mean temperature

ZHAO De-Ming* and WU Jianb

*CAS Key Laboratory of Regional Climate-Environment for Temperate East Asia, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China; bDepartment of Atmospheric Science, Yunnan University, Kunming, China

ABSTRACT
The contributions of urban surface expansion to regional warming over subregions of Shanghai and Shanghai as a whole using different methods to calculate the daily mean surface temperature (SAT), including the averages of four daily time-records (0000, 0600, 1200, and 1800 UTC; $T_d$), eight daily time-records (0000, 0300, 0600, 0900, 1200, 1500, 1800, and 2100 UTC; $T_s$), and the averages of the SAT maximum ($T_{\text{max}}$) and minimum ($T_{\text{min}}$). $T_{\text{env}}$ were compared based on simulated results using nested numerical intergretations with the Weather Research and Forecasting regional climate model, where only the satellite-retrieved urban surface distributions differed between two numerical experiments. The contributions from urban-related warming expressed similar intensities when using $T_d$ and $T_{\text{env}}$, while the smallest values occurred when using $T_s$ over different subregions of Shanghai (with the exception of areas that were defined as urban for both time periods (U2U)) and Shanghai as a whole. Similar values for the changing trends could be detected over different subregions when no urban surface expansion (EX1) was detected for both $T_d$ and $T_{\text{env}}$. The corresponding values increased under urban surface expansion (EX2) and varied over different subregions, revealing much stronger intensities over urban-surface expansion areas; the weakest intensities occurred over U2U areas. The increasing trends for EX2 and relative contributions when using $T_s$ were smaller than when using $T_d$ with the exception of those over U2U areas, which could be explained by the changing trends in $T_{\text{max}}$ and $T_{\text{min}}$ due to urban surface expansion, especially during intense urban expansion periods.

1. Introduction

Daily mean surface air temperature (SAT) is an important factor to evaluate climate change. It is essential that SAT must be correctly calculated. However, due to the natural variability of the climate system and intense economic development and anthropogenic activities, including the greenhouse effect, aerosol emissions, and land-use and land-cover changes (e.g., urban surface expansion), SATs calculated using different methods can differ (Ye, Xie, and Liu 2002), which might have an impact on climate change evaluations.

In general, daily mean SAT is defined by the averages of continuous values during a 24-hour period; however, it is usually calculated using hourly values instead (e.g., three (0000, 0600, and 1200 UTC; $T_d$), four (0000, 0600, 1200, and 1800 UTC; $T_s$) or eight (0000, 0300, 0600, 0900, 1200, 1500, 1800, 2100 UTC; $T_{\text{env}}$) times a day) (Tang and Ding 2007). Due to historical limitations, SAT values are usually observed three or four times a day from meteorological stations in China (China Meteorological Administration 2007), while SAT maximum ($T_{\text{max}}$) and minimum ($T_{\text{min}}$) values are mostly recorded over a long-term period (Miller 1953). Therefore, $T_d$ or the averages of $T_{\text{max}}$ and $T_{\text{min}}$ ($T_{\text{env}}$) are usually used to calculate the daily mean SAT.

As the national economic center and the core area for one of the six largest city clusters in the world (Tu 2015), the urban surface of Shanghai has expanded considerably, and the population has increased markedly over the last several decades (Shanghai Municipal Bureau of Statistics 2017),
especially in the past 30 years. The land-use and land-cover changes have a potential impact on land–atmosphere interactions, which might in turn have effects on the SAT. Therefore, considerable impacts on the diurnal cycle, such as the occurrences of $T_{\text{max}}$ and $T_{\text{min}}$ (which express obvious asymmetry (Houghton, Ding, and Griggs et al. 2001)), might be detected. The impacts of intense urban surface expansion on $T_{\text{max}}$ have been found to be much stronger than those on mean SAT (Trusilova et al. 2007). Therefore, SATs calculated with different methods can vary, which might impact evaluations on the contributions of urban surface expansion to regional warming over Shanghai and its corresponding subregions.

In contrast to the limitations of historical observations, numerical experiments using regional climate models can provide SAT values at fine-resolution spatiotemporal scales, which can then be adopted to perform intercomparisons among different methods when calculating daily mean SAT. As an example, the differences in changing trends and relative contributions between $T_d$ and $T_{\text{xn}}$ in Beijing can be attributed to the variance in increasing trends between the changes in $T_{\text{max}}$ and $T_{\text{min}}$ and the daily mean SAT due to urban surface expansion, especially over urban-expanded areas and during intense expansion periods. Therefore, further analysis should be performed to compare the changing trends in SAT and the corresponding relative contributions between $T_4$ and $T_{\text{xn}}$ due to urban surface expansion over the subregions of Shanghai.

Nested integrations based on satellite-derived urban surface distributions over China with a fine resolution over eastern China, especially over three city clusters (Beijing–Tianjin–Hebei (BTH), the Yangtze River Delta (YRD), and the Pearl River Delta (PRD) (Jia et al. 2014; Hu et al. 2015)), were performed to detect the impacts of urban surface expansion on the changing trends in annual mean SAT and their corresponding relative contributions using different methods ($T_{\text{dx}}, T_{\text{bx}}$, and $T_{\text{xn}}$), where fine resolutions at a 6-h interval and 3-h interval and $T_{\text{max}}$ and $T_{\text{min}}$ were adopted to conduct the comparisons.

2. Numerical experiments and data

The numerical experiments and data used during the integrations were the same as those in Zhao and Wu (2018), in which the contributions of urban surface expansion to regional warming in Shanghai were explored using $T_b$. Here, comparisons for the evaluation on urban-related warming using different methods ($T_{\text{dx}}, T_{\text{bx}}$, and $T_{\text{xn}}$) when calculating daily mean SAT were performed over the subregions of Shanghai and Shanghai as a whole.

The coarse domain for the numerical experiments covered most parts of East Asia, within which the first nested domain covered eastern China, and the remaining three domains were located over the three city clusters (BTH, YRD, and PRD) (Figure S1(a)). The geographical location and topographical distributions for the YRD and Shanghai are displayed in Figures S1(b,c).

To detect the impacts of urban surface expansion on regional warming during the past 30 years, long-term numerical integrations using the Weather Research and Forecasting (WRF) regional climate model (Skamarock et al. 2008) were performed, where the only differences occurred in urban surface distributions based on the population information, multiple-source satellite-retrieved images, the National Land Cover Datasets from the Chinese Data Sharing Infrastructure of Earth System Science, and the nighttime light datasets from the Defense Meteorological Satellite Program-Operational Linescan System (Jia et al. 2014; Hu et al. 2015). The first experiment was based on fixed-in-time urban data in the early 1980s (EX1), while the second experiment was established based on reconstructed annual urban data (EX2; Section 2 of the Supplemental Material). Integration restarts were conducted for each year from 1 July of the year prior (used as the spin-up time), where only the integrated results for the present year were discussed.

The physical schemes involved in the numerical integrations are displayed in Section 1 of the Supplemental Material. Reconstruction of the annual urban gridded data is detailed in Section 2 of the Supplemental Material. The driving data, including the initial and time-varying boundary conditions, for the numerical integrations were provided by the NCEP–DOE AMIP-II reanalysis dataset (Kanamitsu et al. 2002; details displayed in Section 3 of the Supplemental Material).

3. Results

3.1. Comparisons of increasing trends using different methods

The increasing trends in annual mean SAT with daily mean values calculated using different methods for EX1 and EX2 and the relative contributions of urban-related warming over the subregions of Shanghai (i.e., areas that are defined as urban for both time periods (U2U), areas that are transformed from nonurban to urban (N2U), and urban areas (including U2U and N2U)) and Shanghai as a whole are shown in Table 1. For EX1, the changing trends calculated using $T_{\text{xn}}$ were close to those using $T_d$ and $T_b$ (Zhao and Wu 2018) over different subregions of Shanghai and Shanghai as a whole. However, for EX2, the changing trends using $T_4$...
were smaller than those using $T_{\text{n}}$ and $T_{\text{D}}$, with the exception of those over U2U areas. As a result, the relative contributions of urban surface expansion to regional warming revealed similar values when using $T_{\text{D}}$ and $T_{\text{n}}$, while the smallest values occurred when using $T_{\text{D}}$ with the exception of trends over U2U areas, where the contributions using $T_{\text{D}}$ and $T_{\text{n}}$ were smaller than those using $T_{\text{D}}$.

### 3.2. Differences in urban-related warming using different methods

Time series of the differences in urban-related warming between $T_{\text{D}}$ and $T_{\text{n}}$ ($T_{\text{n}} - T_{\text{D}}$), $T_{\text{D}}$ and $T_{\text{B}}$ ($T_{\text{B}} - T_{\text{D}}$), and the corresponding changing trends over different subregions of Shanghai and Shanghai as a whole are shown in Figure 1.

The differences between $T_{\text{D}}$ and $T_{\text{n}}$, and the increasing trends over Shanghai as a whole, in the N2U and urban areas were 0.00209, 0.0166 and 0.0153°C, respectively, whereas the differences over the U2U areas were −0.00668°C per decade, which revealed bigger contributions over Shanghai as a whole, in the N2U and urban areas, and smaller values over U2U areas when using $T_{\text{n}}$ due to similar changing trends for EX1 between $T_{\text{D}}$ and $T_{\text{n}}$ (Table 1 and Figure 1(a)).

For the results between $T_{\text{D}}$ and $T_{\text{B}}$, the changing trends for EX1 were quite close when using $T_{\text{D}}$ and $T_{\text{B}}$ (Table 1 and Figure 1(b)); however, the differences in the corresponding values for EX2 were greater when using $T_{\text{B}}$ with the exception of the smaller value over U2U areas. Therefore, bigger contributions could be detected from $T_{\text{B}}$, although the changing trends for the differences over U2U (−0.00394°C per decade) were different from those over Shanghai as a whole, N2U and the urban areas (0.00402, 0.0194, and 0.0181°C per decade, respectively), which could be attributed to stronger changing trends when using $T_{\text{D}}$ for EX2 and greater differences between $T_{\text{D}}$ and $T_{\text{B}}$ (except for U2U areas).

### 3.3. Differences when using $T_{\text{D}}$ and $T_{\text{n}}$

#### 3.3.1. Spatial differences

The spatial distributions of urban-related warming when using $T_{\text{D}}$, $T_{\text{B}}$, $T_{\text{n}}$, and the differences of $T_{\text{D}}$ and $T_{\text{n}}$ ($T_{\text{n}} - T_{\text{D}}$) between EX1 and EX2 and their corresponding differences over Shanghai are displayed in Figure S2, where similar distributions were detected when using $T_{\text{D}}$, $T_{\text{B}}$ and $T_{\text{n}}$, with the exception of several areas that did show differences.

#### 3.3.2. Averages when using $T_{\text{D}}$

The time series of annual mean SAT that was calculated using $T_{\text{D}}$ and the changing trends over different subregions of Shanghai for EX1 and EX2 are shown in Figure 2(a, c, e, and g), which passed the 90%, 95%, 99%, and 99% confidence level (t-tests), respectively. Similar values for the changing trends could be detected over different subregions for EX1, which ranged between 0.0524 and 0.0535°C per decade. However, the corresponding values increased and varied over different subregions for EX2, revealing much stronger intensities over urban-surface expansion areas (0.899 and 0.883°C per decade).

![Figure 1](image1.png)

**Figure 1.** Time series of the differences in urban-related warming between (a) $T_{\text{D}}$ and $T_{\text{n}}$ ($T_{\text{n}} - T_{\text{D}}$), (b) $T_{\text{D}}$ and $T_{\text{B}}$ ($T_{\text{B}} - T_{\text{D}}$), and the corresponding changing trends over different subregions (i.e., the whole area, U2U, N2U, and urban areas) of Shanghai.
decade over N2U and urban areas, respectively), and the weakest values occurred over U2U areas (0.633°C per decade). As a result, the changing trend over Shanghai as a whole was 0.671°C per decade.

3.3.3. Averages when using $T_{xn}$

A time series of the annual mean SAT calculated by using $T_{xn}$ and the changing trends over different subregions ((a, b) whole areas; (c, d) U2U; (e, f) N2U; (g, h) urban areas) of Shanghai for EX1 and EX2 are shown in Figure 2(b, d, f, h), which passed the 90%, 90%, 99%, and 99% confidence level (t-tests), respectively. Similar values of the changing trends could also be detected over different subregions for EX1, ranging between 0.0525 and 0.0538°C per decade. However, corresponding values increased and varied over different subregions for EX2, which revealed much stronger intensities over urban-surface expansion areas (0.919 and 0.902°C per decade over N2U and urban areas, respectively) and weaker intensities over U2U areas (0.631°C per decade). As a result, the changing trend over Shanghai was 0.675°C per decade.

Figure 2. Time series of annual mean SAT calculated using (a, c, e, g) $T_A$ and (b, d, f, h) $T_{xn}$, and the changing trends over different subregions ((a, b) whole areas; (c, d) U2U; (e, f) N2U; (g, h) urban areas) of Shanghai for EX1 and EX2.
3.4. Averages when using $T_{xn}$ due to changes in $T_{max}$ and $T_{min}$

Time series of annual mean SAT calculated using $T_{xn}$ and its changing trends could be further interpreted by changes in $T_{max}$, $T_{min}$, and the diurnal temperature range (DTR) due to urban surface expansion.

3.4.1. Changes in $T_{max}$, $T_{min}$ and DTR

Time series of the changes in $T_{max}$, $T_{min}$, and DTR, and the corresponding trends between EX1 and EX2 over different subregions of Shanghai, are shown in Figure 3.

Time series of the changes in $T_{max}$ over different subregions were similar. The corresponding trends were quite small over U2U, N2U, and urban areas, ranging between 0.0193 and 0.0403°C per decade, whereas the changing trend over all of Shanghai was weak and negative ($-0.00855$°C per decade).

Time series of the changes in $T_{min}$ over different subregions were similar for all of Shanghai and the U2U, N2U, and urban areas, respectively; the corresponding trends were quite small over the two former areas (0.286 and 0.174°C per decade), whereas the trends were much stronger over the latter two areas (0.762 and 0.730°C per decade).

As a result, the time series for the changes in DTR over different subregions were quite opposite to those showing the changes in $T_{min}$ due to the relatively weaker changes in $T_{max}$ which also indicated similar values for Shanghai as a whole and the U2U, N2U and urban areas, respectively. The corresponding trends were smaller over the two former areas (0.294 and 0.134°C per decade, respectively) and much stronger over the latter two areas (0.743 and 0.709°C per decade, respectively).

Differences in the changing trends of $T_{max}$, $T_{min}$ and DTR between EX1 and EX2 could be further explained by the time series of the corresponding variables for EX1 and EX2, as shown in Figure 4.

3.4.2. Maximum SAT

Time series for the annual mean $T_{max}$ in EX1 and EX2 and the corresponding changing trends are shown in Figure 4 (a, c, e and g); the changing trends in EX1 were similar among different subregions and ranged between 0.580 and 0.598°C per decade. The changing trends for EX2 were 0.621, 0.617, and 0.619°C per decade over the U2U, N2U, and urban areas, respectively, and contributed to a changing trend of 0.588°C per decade over Shanghai as a whole. Therefore, urban-related warming accounted for 6.6%, 3.1%, and 3.6% of the total warming over the U2U, N2U and urban areas, respectively. However, the contribution of Shanghai as a whole was weak and negative.

3.4.3. Minimum SAT

Time series of the annual mean $T_{min}$ for EX1 and EX2 and their corresponding changing trends are shown in Figure 4 (b, d, f, and h); the changing trends for EX1 were similar

![Figure 3](image-url). Time series of the changes in (a) $T_{max}$, (b) $T_{min}$, and (c) DTR, and the corresponding trends when using $T_{xn}$ for EX1 and EX2, over different subregions (U2U, N2U, and urban areas) and for Shanghai as a whole.
among different subregions, ranging between 0.463 and 0.478°C per decade. The changing trends for EX2 were greater, with a trend of 0.652°C per decade over U2U, and the trends were much stronger over N2U (1.23°C per decade) and urban areas (1.19°C per decade), which contributed to a changing trend of 0.764°C per decade over Shanghai as a whole. Therefore, urban-related warming accounted for 26.7%, 62.4%, and 61.0% of the total warming over the U2U, N2U, and urban areas, respectively, which contributed to an increasing trend (37.4%) over Shanghai as a whole.

4. Discussion and conclusions

The contributions of urban surface expansion to regional warming over Shanghai by using different methods ($T_A$, $T_B$, and $T_{an}$) to calculate the daily mean SAT were compared with the simulated results that were
dependent on nested numerical integrations using the WRF regional climate model; only the urban surface distribution differed.

The relative contributions of urban-related warming revealed similar values when using $T_b$ and $T_{xn}$, while the smallest values were observed when using $T_4$ (with the exception of U2U areas). These differences could be explained by the similar changing trends for EX1; whereas, smaller changing trends were observed when using $T_4$ compared to those using $T_{xn}$ and $T_b$ for EX2, due to the urbanization-influenced diurnal SAT variations, i.e., the emergence times of $T_{max}$ and $T_{min}$ (Yang, Xiao, and Liu 2013). Differences in changing trends between $T_4$ and $T_{xn}$ revealed larger contributions over U2U areas and smaller values over the other three areas when using $T_4$. Meanwhile, differences between $T_4$ and $T_b$ showed that larger contributions could be detected when using $T_b$, with the exception of those over U2U areas.

Similar values for changing trends could be detected over different subregions for EX1 when using $T_4$ and $T_{xn}$. The corresponding values increased for EX2 and varied over different subregions, revealing much stronger intensities over urban-surface expansion areas and weaker intensities over U2U areas. However, the increasing trends for EX2 when using $T_4$ were smaller than those when using $T_{xn}$, with the exception of those over U2U areas.

Differences between $T_4$ and $T_{xn}$ could be explained by the changes in $T_{max}$ and $T_{min}$ due to urban surface expansion, especially during intense urban expansion periods. The increasing trends in the changes in $T_{max}$ over different subregions were similar for both EX1 and EX2. However, the corresponding values for the changes in $T_{min}$ were similar between Shanghai as a whole and U2U (smaller), and N2U and urban areas (larger), respectively. For the changes in $T_{max}$ urban-related warming accounted for 6.6%, 3.1%, and 3.6% of the total warming over the U2U, N2U, and urban areas of Shanghai, respectively. The value over Shanghai as a whole was negative. However, for the changes in $T_{min}$ urban-related warming accounted for 26.7%, 62.4%, and 61.0% of the total warming over the U2U, N2U, and urban areas, respectively; and contributed to 37.4% of the total warming over Shanghai as a whole. Therefore, changes in the DTR over different subregions were opposite to those in $T_{min}$ due to the small changes in $T_{max}$ and the intense changes in $T_{min}$.

The increasing trends in SAT calculated using $T_4$, $T_b$, and $T_{xn}$ were quite similar over the subregions of Shanghai; however, the corresponding values over Beijing were quite varied, showing marked subregional characteristics, which could be explained by comparing the increasing trends in $T_{max}$, $T_{min}$, $T_{xn}$, $T_4$, and $T_b$ for EX1 and EX2 over the urban areas of Shanghai and Beijing, as shown in Figure 5.

In general, the increasing trends in $T_4$, $T_b$, and $T_{xn}$ for EX1 over the urban areas of Shanghai were greater than those over Beijing, whereas the corresponding values for EX2 over Shanghai were smaller than those over Beijing. Therefore, the relative contributions of urban-related warming to regional warming over Shanghai were weaker than those over Beijing.

For the urban areas of Beijing, for example (Figure 5), smaller values of the changing trends in $T_{max}$ and larger values of the changing trends in $T_{min}$ induced a weak trend in $T_{xn}$ for EX2, though the increasing trend in $T_{min}$ for EX2 was much greater than that for EX1. As far as the increasing trends over the urban areas of Shanghai were concerned, the increasing trend by using $T_{xn}$ was almost the same as those by using $T_4$ and $T_b$ for EX2, which could be attributed to the larger trend in $T_{max}$ (compared to the value over urban areas of Beijing), although the trend in $T_{min}$ over the urban areas of Shanghai was smaller than that over Beijing.

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