Satellite-Derived Subsurface Urban Heat Island

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* Supporting Information

ABSTRACT: The subsurface urban heat island (SubUHI) is one part of the overall UHI specifying the relative warmth of urban ground temperatures against the rural background. To combat the challenge on measuring extensive underground temperatures with in situ instruments, we utilized satellite-based moderate-resolution imaging spectroradiometer data to reconstruct the subsurface thermal field over the Beijing metropolis through a three-time-scale model. The results show the SubUHI’s high spatial heterogeneity. Within the depths shallower than 0.5 m, the SubUHI dominates along the depth profiles and analyses imply the moments for the SubUHI intensity reaching first and second extremes during a diurnal temperature cycle are delayed about 3.25 and 1.97 h per 0.1 m, respectively. At depths shallower than 0.05 m in particular, there is a subsurface urban cool island (UCI) in spring daytime, mainly owing to the surface UCI that occurs in this period. At depths between 0.5 and 10 m, the time for the SubUHI intensity getting to its extremes during an annual temperature cycle is lagged 26.2 days per meter. Within these depths, the SubUHI prevails without exception, with an average intensity of 4.3 K, varying from 3.2 to 5.3 K.

INTRODUCTION

Urban heat islands (UHIs) exhibit different forms associated with at least four parts: the boundary-layer urban heat island (BLUHI), canopy UHI (CUHI), surface UHI (SUHI), and subsurface UHI (SubUHI).1 The past decades have been witnessing the investigation of the former three types of UHI. Comparatively, the SubUHI was less studied and poorly understood, mostly because of the lack of measurements, though attempts of gauging subsurface temperatures have been conducted by Abbe Mariotte at least since 1670.2 The investigation of SubUHI has multiple environmental applications.3−5 Analyzing the spatiotemporal patterns of the SubUHI is also one crucial step toward understanding the UHI mechanism across the entire vertical profile from the atmospheric boundary layer to deep subsurface soil.

Similar to the BLUHI, the SubUHI is vertically different. We therefore categorize the previous studies on SubUHI into the following three layers: (1) the very-deep layer (deeper than 100 m), (2) the deep layer (between 10 and 100 m), and (3) the shallow layer (between 0 and 10 m). The soil temperatures at these three layers are correspondingly impacted by surface climate approximately related to centenary, decadal, and annual cycles, respectively. At the very-deep layer, subsurface temperatures measured in deep boreholes are good indicators of historical surface climate6,7 and land cover change,8 particularly, the urbanization.9 At this layer, the SubUHI develops over time scales of a century or more.10−12 At the deep layer, Ferguson and Woodbury3 indicated that the relationship between soil temperature and surface processes is complex. Menberg et al.13,14 stressed the importance of anthropological heat sources, such as the excessive urban hotspots against their surroundings due to the impact from manmade subsurface geothermal systems. At the shallow layer, the SubUHI varies diurnally and seasonally.4,15−18

Received: April 30, 2014
Revised: September 1, 2014
Accepted: September 15, 2014
Published: September 15, 2014
Although the investigation of SubUHI has been progressing, most current studies were performed using soil temperatures measured within sparsely distributed wells. High spatial heterogeneity of SubUHI has been shown at the deep layer;

at the shallow layer, the spatial heterogeneity of SubUHI is expected to be greater. Unfortunately, the sparsely distributed wells, as well as their high cost to install a dense observation network, make it difficult to characterize this spatial heterogeneity. Thermal remote sensing, a technique capable of obtaining extensive land surface temperatures (LSTs) at a spatial resolution of 100–1000 m and widely used in monitoring the SUHI,\textsuperscript{19} is a good option for tackling the heterogeneity challenge. Zhan et al.\textsuperscript{20} showed that subsurface temperatures can also be estimated using observations using the moderate-resolution imaging spectroradiometer (MODIS). To our knowledge, this is the first study in an effort to detect SubUHI by remote sensing.

**STUDY AREA**

The Beijing municipality, including urban Beijing and its surrounding suburban and rural areas, was selected as the study area (Figure S1). Situated in the eastern end of Eurasia, Beijing locates at the northern tip of the North China Plain. The prevalent temperate continental monsoon climate is characterized by four distinctive seasons, with hot and humid summers dominated by the East Asian monsoon but cold, dry, and windy winters influenced by the Siberian anticyclone.\textsuperscript{21} Beijing had a population of 21.15 million in late 2012, and the population density over its core districts (including the Dongcheng, Xicheng, Chongwen, and Xuanwu District) is about 20 000–30 000 people/km$^2$.\textsuperscript{22} The dense urbanization has had severe climate and environmental effects. The CUHI intensity over Beijing has increased by between 0.25 and 0.31 K per decade in the past four decades.\textsuperscript{23,24}

**METHOD**

Assumptions. Urban surface and substrates are characterized by high complexity. Remote sensing is the only tool to observe extensive and complex urban surface temperatures (USTs), but its associated low spatial resolution makes it difficult to parametrize the detailed urban geometry. Three assumptions are required when thermal remote sensing is employed to investigate the SubUHI. (1) Remotely sensed LSTs represent the true surface temperature. (2) Urban surfaces are simplified to be flat, with vegetation scattered at the top. (3) Heat conduction is the major heat transfer process within urban substrates. Detailed clarifications on these three assumptions are given as section 1 in the Supporting Information (SI).

**Three-Time-Scale Model.** The three-time-scale (3-scale) model, developed by Zhan et al.\textsuperscript{20} was used to estimate subsurface temperatures. It incorporates three temporal cycles: the annual temperature cycle (ATC), weather-change temperature cycle (WTC), and diurnal temperature cycle (DTC). This model is able to produce soil temperatures up to a depth of around 10 m. It uses the following formula:

$$T(z,t) = f(T_s, T_0, \Delta T_{atm}, \Delta T_{w}, \Delta T_{v}, h, \phi, \omega, \sigma, z, t)$$

where $z$ and $t$ denote the depth and time, respectively; $T_s$ is the subsurface temperature; $T_0$ is the annually averaged temperature; $\Delta T_{atm}$ and $\Delta T_{v}$ represent the daily average temperature, which denote the harmonic temperature variations in an ATC and the temperature variations due to weather change, respectively; $\Delta T_{w}$ and $\Delta T_{v}$ represent the instantaneous temperatures and denote the diurnal temperature variations and the day-to-day temperature difference due to weather change, respectively.

According to section 2 from the SI, subsurface temperatures $T(z, t)$ can be further given as

$$T(z, t) = f(T_s, A_t, \Delta H, h, P, \sigma, z, t)$$

where the seven unknown parameters $T_s, A_t, \Delta H, h, P, \sigma, \Delta T_s$ and $\phi$ represent the annually averaged temperature, ATC amplitude, phase offset, daily averaged LSTs, coefficient of upward heat flux, thermal inertia, and change rate of the day-to-day temperature difference, respectively, with the latter four varying from day to day. Over a DTC, the daily variables, $T_0, h, P$, and $\sigma$ can be estimated using four instantaneous satellite-derived LSTs for a diurnal cycle. Over an ATC, daily $T_0$ are then combined to estimate $T_s, A_t, h, P$, and $\phi$. These determined seven coefficients (i.e., the four DTC parameters plus the three ATC parameters) enable the estimation of subsurface temperatures through eq 1.

**Model Forcing and Validation Data.** To drive the 3-scale model, satellite products of LSTs and vegetation indices are required. MODIS operational products are used to force the model over the Beijing municipality in 2012. They include MOD11A1, MYD11A1, MOD13A2, MCD15A2, and MCD43B3. Details on the introduction and processing of these products are given in section 3 of the SI. Daily soil temperatures at 0.05, 0.40, and 3.20 m that were measured at seven ground-based sites (see Table S2) were used for validation.

**SubUHI Intensity (SubUHII) and Its Dynamics.** UHI intensity (UHII) is an important parameter to quantify UHII status. This study calculates the SubUHI as the difference between the subsurface temperature at a certain urban pixel and those averaged within the chosen rural background area (Figure S1), given as follows:

$$\text{SubUHII}(z, t) = T_s(z, t) - T_r(z, t)$$

where $T_s$ and $T_r$ are the subsurface temperatures at a certain urban pixel and within the rural background area, respectively.

To investigate the dynamics of SubUHII, we provide the time delay ($t_{\text{delay}}$) of SubUHII for achieving the maximum along the DTC and ATC between two different depths. The theoretical expression for estimating $t_{\text{delay}}$ is complex, but it can be simplified as follows once the surface temperature cycle is harmonic (the proof is given in section 4 in the SI):

$$t_{\text{delay}} = \left(2\pi\right)^{-1} \frac{1}{P} N \Delta z \sqrt{\omega / 2D}$$

where $t_p$ is the seconds of a day; $N$ is the number of days in the corresponding cycle, it is equal to 1 for a DTC and 365 for an ATC; $\Delta z$ is the depth difference; $\omega$ is calculated by $2\pi / t_p$ for a DTC and by $2\pi / (365 t_p)$ for an ATC; and $D$ is the thermal diffusivity.

The diurnal variation of surface energy fluxes can penetrate the ground downward up to the depth of about 0.5 m (termed as the zero diurnal range, ZDR); whereas the annual variation of surface fluxes has an impact on the soil thermal status at depths up to the zero annual range (ZAR).\textsuperscript{25} The ZAR depends on soil thermal properties and climatic conditions, and a representative value is about 10 m for typical land surfaces.\textsuperscript{25} The spatiotemporal SubUHI is thus offered for two separate
depth ranges: the shallow-layer (ZDR, 0 < \(z\) < 0.5 m) which is regulated by the DTC and ATC and the deep-layer (ZAR, 0.5 < \(z\) < 10 m) which is primarily governed by the ATC.

**VALIDATION AND RESULTS**

The subsurface temperatures estimated using the 3-scale model are validated with measured soil temperatures at seven ground-based sites. The results are given in Figure 1. To demonstrate the temporal accuracy across an ATC, the validation of daily soil temperatures at the Haidian site is also provided (see Figure 1b). The overall averaged MAE at all sites is 1.54 K (more details on the MAE at each site can be found in Table S3). This mismatch is possibly due to the following aspects: (1) the scale difference between satellite observation and ground-based measurements, which implies that the objects these two techniques observe are not the same, (2) the error of MODIS/LST product, the accuracy of which is reported around 2 K but is likely to increase over urban areas as a result of significant urban thermal anisotropy.

**SubUHI within ZDR (0 m < \(z\) < 0.5 m).** The four clear-sky days DOY 024, 107, 235, and 284 in 2012 were chosen to represent winter, spring, summer, and autumn, respectively. These four days were selected because they had the largest

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**Figure 1.** Validation of the estimated subsurface temperatures. Part a shows the comparison between the observed and estimated temperatures at 0.05, 0.40, and 3.20 m at the seven sites, and part b provides the temporal comparison between the observed and estimated daily temperatures at the Haidian site.

**Figure 2.** Spatiotemporal variation of the subsurface UHI at five shallow depths (i.e., 0.01, 0.02, 0.10, 0.20, and 0.40 m) and four times in a diurnal cycle (i.e., 14:00, 20:00, 02:00, and 08:00) on DOY 024, 107, 235, and 284.
number of valid (i.e., cloud-free) pixels during the corresponding seasons.

Within the ZDR, the spatiotemporal SubUHI is displayed at five depths and presented at four times of day (see Figure 2). The SubUHI effect was observed at all times and depths except for very few, e.g., the first row (14:00 h) on DOY 024 and 107. This almost-omnipresent heat island confirms previous studies, e.g., those of Yalcin and Yetemen\textsuperscript{17} and Tang et al.\textsuperscript{15} showing that the land cover conversion from natural to urban surfaces does have an impact on both the LST and shallow-layer subsurface temperatures. The SubUHI configuration, illustrated as the SubUHII and spatial extent, has a high variation (Figure 2).

In winter, the maximum and minimum SubUHI within the ZDR are 6.9 K (time 02:00; depth 0.01 m) and −0.4 K (time 14:00; depth 0.01 m), respectively, which means that no heat island occurs at the first few subscenes of Figure 2. The SubUHI in several of the scenes have an unenclosed shape, with a well-defined UHI “tail” stretching to the southwest of Beijing. This is probably because of the harvested arid cropland between the primary urban center and the satellite city center (Fangshan), which shows high surface temperatures and thus bridges these two city centers. In spring, the maximum SubUHI within the ZDR is 3.2 K (time 14:00; depth 0.4 m). At 14:00, a subsurface urban cool island (SubUCI), which denotes the urban center is colder than its rural background, occurs at very shallow depths, and the spatial extent of SubUHI gradually increases with depth. This is natural because a surface urban cool island (SUCI) was also observed over Beijing in spring.\textsuperscript{27} The SubUCI and SUCI are probably caused by the increased surface temperature in rural areas where bare soil dominates as vegetation is still in its germination.

In summer, the SubUHI prevails at all times and depths with no exception. The maximum SubUHII and spatial extent both emerge at the first scene of Figure 2c (time 14:00; depth 0.01 m), with the maximum intensity of 10.4 K and the maximum spatial extent outstripping the boundary of Beijing. The minimum SubUHII appears at the time of 08:00 and the depth of 0.02 m, with the intensity of 2.2 K. In summer daytime, the higher evapotranspiration over rural areas than over urban areas results in a much higher LST over urban areas than its surrounding rural ones. Anthropogenic heat produced from air conditioning and ground source heat pumps in summer also contributes to the increase of USTs and thus to the increase of subsurface temperatures, which leads to a significant SubUHI in shallow layers. During autumn, the intensity and spatial extents of SubUHII at the different times and depths are analogous to those during summer, despite the absolute urban and rural LSTs having a high variation.

To assess the SubUHII variation with the time and depth, four continuous contours on the relationship between the intensity and the time and depth are shown in Figure 3. The extreme values of the SubUHI and SubUCI intensity are 8.5 and −3.4 K, respectively, occurring at 15:00 and 0.0 m on DOY 235 and occurring at 13:00 and 0.0 m on DOY 024, respectively. The SubUHI at the surface (depth = 0.0 m) is in fact equal to the SUHI when aboveground vegetation is absent, i.e., the SubUHI at 0.0 m refers to the model output at the surface but is still termed as “subsurface” in this context. These assessments imply that the SubUCI does account for a very small part, occurring only at a very thin layer (the depth shallower than 0.05 m) in a short period (at around 14:00).

On DOY 024, 235, and 284, one hot spot and one cold spot are observed, both with their extreme values at the surface (i.e., $z = 0$). This suggests that the diurnal variation of SUHI is higher than that of the SubUHI, but this does not mean that the SUHI intensity is always more significant than that of the SubUHI. Assuming that the LST in a clear-sky DTC changes harmoniously, the time delay ($t_{\text{delay}}$) of the soil temperatures at two depths, according to eq 4, is calculated as 3.26 h when the depth difference (i.e., $\Delta z$) is 0.1 m. This value is almost equal to the time delay (i.e., 3.25 h, see Figure S4) for the SubUHII getting to its first extreme, because the daytime LST variation in a clear-sky does follow a quasi-harmonic function.\textsuperscript{28} For the second extreme, the LST during nighttime decreases exponentially. The nonharmony of the exponential function makes the time delay (i.e., 1.97 h) no longer equal to the theoretically deduced $t_{\text{delay}}$ (i.e., 3.25 h) estimated using eq 4.

SubUHI within ZAR (0.5 < $z$ < 10 m). Within the ZAR, to obtain the representative SubUHI status, we provide the seasonally averaged spatiotemporal SubUHII at five depths during spring, summer, autumn, and winter (Figure 4). The

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**Figure 3.** Variation of the SubUHI intensity with the time of day and virtual depth at the city center (i.e., Qianmen). Cases of DOY (a) 024, (b) 107, (c) 235, and (d) 284, respectively. Note that the diurnal cycle starts at 12:00. Arrows A and B are two gentlest descending and ascending directions from the hot or cold spots.
SubUHI prevails in all cases, indicating that the short-lived SubUCI during daytime in winter and spring has insignificant impact on deep-layer heat island. The minimum and maximum SubUHII occurs at 0.5 m during spring and winter, respectively. The difference between maximum and minimum SubUHII is small, considering that subsurface temperatures range from 267 to 301 K during an ATC at depths between 0.5 to 10.0 m. The SubUHI at 5.0 and 10.0 m is found rarely impacted by season. The estimated SubUHII is similar to those in several German cities, which ranges from 3 to 5 K.13 The intensity found in Beijing is higher than that estimated in several east Asian cities,10 where it is approximately 2 K. The case studies in Beijing and the German cities were conducted at 10-m depth or less, within which the intensified urbanization in recent years contributes more to the subsurface thermal environment; by contrast, the subsurface temperatures used in the work of Taniguchi et al.10 were obtained at 100-m depth. It is expected that at a layer deeper than 10 m, the SubUHII for Beijing is also smaller.

The SubUHII variations with day of year and depth are shown in Figure 5, in which daily averaged temperature is taken as the target parameter and short-term weather change is ignored in order to analyze the SubUHI climatically. The results demonstrate that the SubUHII ranges from 3.2 to 5.3 K, both occurring at the depth of 0.5 m. In analogy to the variation of the SubUHII during a DTC (see Figure 3), one hot and one cold spot are observed in an ATC. The cold spot appears in late spring and early summer, probably due to the impact from the surface UCI that prevails in winter and spring daytime. The hot spot emerges in later autumn and early winter, which may be a combined effect of (1) daytime surface UHI significant enough before being converted into a surface UCI in winter and (2) the increased nighttime UHI resulted from anthropogenic heat produced by heating power supplies that begins in later autumn. This temporal behavior is different from the preceding observations on the SUHI (1) that daytime intensity strengthens in summer but sinks in winter and (2) that nighttime intensity increases in winter but weakens in summer.

The temperature contours in Figure 5b further indicate that the annual SubUHII evolutions at different depths follow a harmonic function. However, the annual SubUHII amplitude in deeper layers is lower than in shallower layers, which is similar

![Figure 4. Subsurface UHI at five deep depths (i.e., 0.50, 1.00, 2.00, 5.00, and 10.0 m) and four seasons in an annual cycle.](image)

![Figure 5. SubUHI intensity variation with the day of year and depth (a) or with the day of year alone at four different depths (b).](image)
to the trend of the SubUHI amplitude in a DTC. A further calculation using eq 4 shows that $t_{\text{delay}}$ is equal to 26.2 days (see Figure 5) for a 1.0 m. This result shows that, for each meter of additional depth, the time at which the hot spot (or cold spot) occurs is delayed by a period slightly shorter than a month.

**DISCUSSION**

**How are the SubUHI and SUHI Related?** The strong relationship between SubUHI and surface landcovers has been noticed in previous studies.\(^3\)\(^8\) The relation between the SUHI and SubUHI at a certain depth is similar to that between the SubUHIs at two different depths. The relations between the SubUHI and SUHI are illustrated from the following three aspects:

1. On the intensity: The SUHI and shallow-layer (0 < z < 0.5 m) SubUHI intensities both vary diurnally but the SubUHI intensity at a greater depth has a less significant variation during a DTC. At deep layers (0.5 < z < 10 m), the SubUHI intensity reflects a combined average of a long-period SUHI. This is interesting because the SubUHI within deep-layers, at which the impacts from the DTC vanishes but those from the ATC increases, provides a climate-based perspective of the temporal evolution of SUHI.

2. On the time-delay: There is a time delay, which depends on the depth difference, between the SUHI and SubUHI intensity reaching their extremes.

3. On the causes: In contrast to the SUHI, which typically results from land cover change from natural to manmade surfaces,\(^19\) the SubUHI is additionally affected by a number of factors that may influence subsurface heat transfer, including groundwater flow and local heat sources.\(^15\)

**Can the SubUHI at a Depth Greater than the ZAR be Remotely Estimated?** This study only investigates the upper boundary (i.e., the layer within the ZAR) status of the SubUHI, and the model period is limited to an annual cycle. The examination of SubUHI at a depth beyond the ZAR would be much more useful to practitioners,\(^6\)\(^12\) but this requires continuous satellite LSTs far beyond an ATC to drive the modeling. Assuming that the ZAR is 10 m, the explorations of the soil thermal status at z m call for satellite LSTs across (z/10)\(^2\) y, according to the heat diffusion theory.\(^29\) This indicates that, for depths between 20 and 100 m one needs surface observations dating back between 4 and 100 y, which means that the archive of the current decade-long MODIS data is able to support analyses of the SubUHI downward to approximately 30 m. AVHRR-derived LSTs have the potential of being used for remote sensing of the SubUHI beneath 30 m. The archive of visible and near-infrared (VNIR) satellite and airborne data may also be useful because the land cover change and accordingly the surface thermal status can be predicted using the VNIR-type data through an indirect way. Satellite remote sensing of the SubUHI beneath 50 to 60 m would be quite difficult regarding the relative short history of collecting remote sensing data on a regular basis.

**What are the Impacts of the Error or Incapability of Satellite-Derived LSTs on the Remotely Sensed SubUHI?** The subsurface temperatures used in this study were estimated with the 3-scale model driven by satellite data. Thus, it is expected that the estimated subsurface temperatures are highly dependent on MODIS/LST. Although the MODIS/LST product generally has a verified high accuracy,\(^30\) this product may deviate from true surface temperature because of urban thermal anisotropy, which is significant when the observation zenith angle is large. Other sources of uncertainty may be from the definition of what is true urban surface temperature, which was discussed in section 1 from the SI.

The Beijing metropolis has been frequently enveloped by heavy smog in recent years especially during winter and spring.\(^31\) This has been reflected in the MODIS/LST product, where the number of cloud-free images has decreased in this season, as smog can be labeled as cloud. Besides the smog effect, snow accumulated during winter significantly changes the thermal regime at the surface and thus it is an effective heat insulator that restrains heat exchange between the cold air and the relatively warmer underground.\(^32\) However, the snow cover is not considered in the 3-scale model, which is only applicable for snow-free days.\(^20\) For Beijing or other cities at a lower latitude, no great problem arises from this shortcoming, as snow is infrequent and usually melts quickly. For high-latitude cities with considerable snow, an adapted thermal regime with snow atop the surface should be incorporated by the 3-scale model.

Nevertheless, thermal remote sensing provides a unique way of obtaining the area-integrated temperatures of surfaces, which is impossible with point measurements. The inaccuracies of satellite-derived subsurface temperatures may be calibrated by the relatively accurate point measurements. Data assimilation has the potential to integrate the preciseness of point measurements and the area information on satellite observations.

**ASSOCIATED CONTENT**

Supporting Information

Clarifications on the three assumptions, clarifications on the three-time-scale model, clarifications on model forcing, proof on the evolution and time-delay of the subsurface urban heat island intensity, and Tables S1–S3. This material is available free of charge via the Internet at http://pubs.acs.org/.

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**Notes**

The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**

This work was supported in part by the National Natural Science Foundation of China (Grant number: 41301360), by the National Natural Science Foundation of Jiangsu Province (Grant number: BK20130566), by the Open Fund of State Key Laboratory of Earth Surface Processes and Resource Ecology (Grant number: 2013-KF-01), and by the National 863 Plan (Grant number: 2013AA122801). The first author is also financially supported by the DengFeng Program-B of Nanjing University.

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