Environmental Research Letters

LETTER

Enhanced sensitivity of the urban heat island effect to summer temperatures induced by urban expansion

Zhen Gao*1, Ying Hou1 and Weiping Chen1,2
1 State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, People’s Republic of China
2 University of Chinese Academy of Sciences, Beijing 100049, People’s Republic of China
* Author to whom any correspondence should be addressed.
E-mail: wpchen@rcees.ac.cn

Keywords: urban heat island, urban expansion, heatwave, sensitivity, surface energy balance

Abstract

A suitable thermal environment is important for the economy, society and public health in urban areas. However, the understanding of the relationship between the urban heat island (UHI) effect and background temperature (T-UHI) is very limited. In this study, the UHI effect induced by the urbanization of the megacity Beijing was investigated using the weather research and forecasting model. Urban expansion and heatwaves both considerably enhanced the UHI effect over urban areas in summer. The strengthened UHI effect during the heatwave period can be clearly explained by the positive sensitivity of T-UHI. The urban expansion increased the sensitivity of T-UHI from 0.0207 °C °C−1 in 2000 to 0.0569 °C °C−1 in 2010 in the daytime and from 0.0715 °C °C−1 in 2000 to 0.0995 °C °C−1 in 2010 at nighttime, thus resulting in a much stronger UHI effect mainly by increasing the difference between the latent heat flux and sensible heat flux. This enhanced sensitivity may exacerbate the urban heat stress in the situation of further urban expansion and background climate warming. Our results suggest that the sensitivity of T-UHI is a meaningful indicator to assess the urban thermal environment change and support the designing of heat mitigation strategies in urban planning.

1. Introduction

Urbanization has been widely occurring around the world, characterized by the dramatic expansion of artificial surfaces (e.g. buildings and roads) and the explosive growth of urban population (Taubenböck et al 2012, Liu et al 2014, UNPD 2014). A considerable impact of urbanization on microclimate is the urban heat island (UHI) effect, which generates higher temperature in urban areas than in suburban or rural areas (Oke 1982, Grimmond 2007). The elevated temperature results in concerns about the urban thermal environmental deterioration, public health issues and economic losses in summer (Frumkin 2002, Tan et al 2010, Laïdi et al 2012, Estrada et al 2017). Therefore, there is a strong motivation to investigate the UHI effect and its dominant influential factors.

Various studies have focused on the changes of the UHI intensity due to the local urbanization (Zhou et al 2004, Zhang et al 2009, Zhang et al 2010, Chapman et al 2017). The urban expansion with conversion of natural/vegetated cover to artificial surfaces has been broadly recognized as the main contributor to greater UHI effect in most cities (Imhoff et al 2010, Zhou et al 2015, Hu et al 2017, Li et al 2017). The rate of warming significantly increases in summer with the expansion of built-up areas (Cao et al 2018). These phenomena are linked to the effects of urban structures and heavy usage of building materials (e.g. concretes and asphalts) on the land surface radiation budget and energy balance, which reduce the latent heat flux and increase the sensible heat flux (Oke 1982, Arnfield 2003). The anthropogenic heat emission as an important source of urban heat also shows a positive relationship with the UHI effect (Shahmohamadi et al 2011). In contrast, green lands, water bodies (Zhao et al 2017, Sun et al 2018), and green roofs (Coutts et al 2013, Santamouris 2014) in urban areas show
Several studies, on the other hand, investigated the impacts of background climate and weather, including heatwaves (Li and Bou-Zeid 2013, Founda and Santamouris 2017, Zhao et al 2018b), rainfalls (Zhao et al 2014, Yang et al 2017) and the wind speed (Morris et al 2001, He 2018), on the UHI effect. Zhao et al (2018b) demonstrated that there exists synergistic effect between the UHI effect and heatwaves in temperate climate cities. The difference between urban and rural areas in evaporation and anthropogenic heat release contributes to the enhanced UHI effect during heatwaves compared to normal days. Such a phenomenon is found in a wide range of cities (Li et al 2015, Schatz and Kucharik 2015, Ramamurthy and Bou-Zeid 2017, Tewari et al 2019). Considering that the heat risks in urban areas are closely relevant to background temperature and the UHI intensity (Gabriel and Endlicher 2011), it is necessary to investigate the relationship between temperature and the UHI effect (T-UHI). However, few studies have explored the variation of the UHI effect in response to increases in background temperature on fine spatial scales. One such piece of research was conducted by Scott et al (2018), who found that the T-UHI relationship varied in different cities which may be positive or negative. Moreover, there is still lack of research on the influence of urban expansion on the T-UHI relationship, which is a major concern associated with the UHI effect issue.

In this study, we aim to explore the way in which the T-UHI relationship results in the UHI effect difference between heatwaves and normal days and how the urban expansion influences this relationship in the context of Beijing, a highly urbanized and densely populated megalopolis. The weather research and forecasting (WRF) model was employed to investigate the characteristics of the T-UHI relationship and its responses to urban expansion. The WRF model is a mesoscale numerical weather prediction system and offers full options for representing atmospheric processes (www.mmm.ucar.edu/weather-research-and-forecasting-model). Because of its nesting capability and ability to be coupled with the urban canopy models, the WRF has been extensively used to simulate the urban micrometeorology with high resolution. Its capacity to capture the temporal-spatial variations of regional climate caused by urbanization have been shown in many studies across a range of cities and climate conditions (Georgescu et al 2014, Cao et al 2016, Wang et al 2016, Krähenhoff et al 2018). The remainder of this paper is organized as follows: section 2 demonstrates the simulations and statistical methods with details. Next, the results and discussions are presented in section 3. Finally, the conclusions and implications are given in section 4.

2. Methods

2.1. Model description and experimental design

We used the WRF-ARW version 3.6.1 (Skamarock et al 2008) coupled with a single-layer urban canopy model (Chen and Dudhia 2001, Kusaka et al 2001) to simulate the regional climate features in Beijing. In this study, three nested domains (figure 1(a)) were configured with spatial resolutions of 1, 3 and 9 km to cover the Beijing metropolitan region, the Beijing–Tianjin–Hebei area, and northern China, respectively and to capture the local major topographic features and continental monsoon climate of the temperate zone. Three sets of simulations (see figure 2) were designed.
to include the hottest months of June–August in two individual years (2000 and 2010), when two of the hottest summers occurred over the past six decades according to observed meteorological records (Sun et al 2014, Cui et al 2017). All experiments’ simulation periods started at 00:00 UTC 21 May and ended at 00:00 UTC 01 September to cover the entire summer and the heatwave periods. The initial ten days (21–30 May) were used as the spin-up time to eliminate the bias of the initial conditions, and the following days were analyzed, except for days when intense rainfall events occurred (total rainfall > 10 mm) due to their uncertain influence on the UHI effect (Yang et al 2017). The time interval of the model outputs is one hour, and the vertical coordinate level is 50, beginning from the surface to 50 hPa pressure. In our simulation, we defined the ERA-interim dataset (Dee et al 2011) with 0.75° × 0.75° spatial resolution and 6 h time interval as the initial boundary conditions of the WRF model as it has a low simulated bias in terms of the temperature pattern in the Beijing area (Yang et al 2016). The main physical parameterization schemes used in this study are summarized in table S1. The sea surface temperature from the ERA-interim reanalysis is also updated every 6 h in the simulation.

Three experiments (named ‘Urban_2000’, ‘Urban_2010’, and ‘NoUrban’, figure 2) were conducted to explore the responses of the UHI effect to urban expansion and heatwaves. Land cover datasets with 30 m resolution for 2000 and 2010 derived from the National Land Cover/Use Dataset of China (NLCD-China, Zhang et al 2014), were aggregated to 1 km spatial resolution (WRF inner scale) based on the dominant land cover approach, and finally were transformed to the US Geological Survey (USGS) 24-category system and three-category urban land cover type (figures 1(b) and (c)). The ‘Urban_2000’ experiment represented the urbanization condition in 2000 and the ‘Urban_2010’ in 2010. In the ‘NoUrban’ experiment, all urban areas were replaced by nearby dominant land cover category (cropland in this study). All three sets were performed with both the 2000 and 2010 meteorological forcing to exclude the influence of annual climate variation. Thus, the differences between ‘NoUrban’ and the other two experiments can be used to present the UHI effect, whose intensity is typically defined as the two-meter air temperature difference ($\Delta T_a$) or the surface temperature difference ($\Delta T_s$).

To evaluate the simulations, the results of the ‘Urban_2000’ and ‘Urban_2010’ experiments with the corresponding boundary conditions were compared with the observed data acquired from meteorological stations and satellite remote sensing data (figures S1 and S2 is available online at stacks.iop.org/ERL/14/094005/mmedia). The simulated air temperature generated by the WRF model agreed well with the observations. And the surface temperature spatial pattern based on simulations reasonably captured the temperature distribution with high temperatures in the urban areas and the north plain areas and low temperatures in the mountainous and hilly areas. The results confirmed that the WRF model performed well in simulating the climatic characteristics of Beijing, although the simulated land surface temperature was higher than the observed data, perhaps because the MODIS LST data usually underestimated the true value (Hu et al 2014).

### 2.2. Identification and attribution of the UHI effect

The definition of a heatwave provided by Meehl and Tebaldi 2004 was used to identify the heatwave events during a certain period. It relies on two thresholds related to the daily maximum temperature ($T_{\text{max}}$) of the period: the 97.5st percentile of $T_{\text{max}}$ and the 81st
percentile of $T_{\text{max}}$. A consecutive air temperature record (from 19600101 to 20101231) of the Beijing WMO station (code: 54511, location: 40.07 °N, 116.59 °E) was used to identify those two thresholds, which were 34.7 °C and 29.6 °C, respectively. Four heatwave events in 2000 (total 30 d: 0612-0621, 0630-0702, 0711-0714, 0720-0801) and three heatwave events in 2010 (total 20 d: 0702-0706, 0720-0731, 0814-0816) were identified and referred to as ‘HW’; the remaining normal days were referred to as ‘ND’, hereinafter.

Following the definition above, we computed the average intensity and investigated the spatial distribution of $\Delta T_a$ and $\Delta T_s$ during the HW and ND periods. To measure the T-UHI relationship, we calculated the linear regression slope of the UHI effect against the background temperature and defined it as the sensitivity of T-UHI, which reflects the change in the UHI intensity in response to a unit increase in background temperature. The sensitivity of $\Delta T_s$ and $\Delta T_a$ against air temperature (termed as $T-\Delta T_s$ and $T-\Delta T_a$, respectively) were estimated using the ordinary least square (OLS) models for both daytime and nighttime over urban area. The Pearson’s correlation coefficients were employed to examine the strength of linear regression analyses while the Student’s t tests were used to judge the significance at the 0.05 level. To evaluate whether the linear regression model of T-UHI can explain the UHI difference between the HW and ND periods, a ‘ratio’ index was calculated as:

$$\text{ratio} = \frac{(\Delta T_{\text{HW,LRM}} - \Delta T_{\text{ND,LRM}})}{(\Delta T_{\text{HW,WRF}} - \Delta T_{\text{ND,WRF}})}$$

where $\Delta T$ refers to the UHI effect ($\Delta T_a$ or $\Delta T_s$). The subscripts ‘HW’ and ‘ND’ represent the different periods, while ‘LRM’ indicates the predicted values from the linear regression models and ‘WRF’ represents the average values from the WRF model.

In addition, we used a simple surface energy balance analysis (Luyssaert et al 2014, Winckler et al 2017, Duveiller et al 2018, Zhao et al 2018a, Liu et al 2019) and the OLS model to reveal the contributions from five biophysical factors, for the purpose of explaining the changes in the sensitivity of T-UHI due to urban expansion. We chose to analyze $\Delta T_a$ instead of $\Delta T_s$ because $\Delta T_s$ is much easier to be approximately derived from the surface energy balance principle. The sensitivity of $T-\Delta T_a$ was estimated as follows:

$$\Delta T_s = \lambda_0(\Delta SW_{\text{net}} + \Delta LW_{\text{down}} - \Delta H - \Delta LE - \Delta G),$$

where $T_s$ is the surface temperature, $\lambda_0 = 1/4\varepsilon\sigma T_s^4$ is Stefan–Boltzmann law, reflecting the local background climate, $\varepsilon$ is the surface emissivity, $\sigma$ is the Stefan–Boltzmann constant, $SW_{\text{net}}$ is the net shortwave radiation, $LW_{\text{down}}$ is the downward longwave radiation, $H$ is the sensible heat flux, $LE$ is the latent heat flux, $G$ is the ground heat flux and $\Delta$ refers to the difference between the urban and reference areas.

3. Results and discussions

3.1. Impact of urban expansion on spatial and temporal variations in UHI effect

The intensive urban expansion, shown in figures 1(b) and (c), resulted in an increasing UHI effect in ‘Urban_2010’ compared with ‘Urban_2000’ (figure 3). The nighttime $\Delta T_a$ was noticeably higher than the diurnal value especially over the highly urbanized region, whereas $\Delta T_a$ displayed the adverse behavior. The spatial distributions of $\Delta T_s$ and $\Delta T_a$ were highly consistent with that of the artificial surface (a local-scale factor, figure S3), but the influence area differences in figure 3 indicates that $\Delta T_s$ was more significantly affected by the regional-scale factor (urban size). The downwind areas where the northern suburban areas (e.g. CP and SY) were located, exhibited a clearer urban warming signal than the

![Figure 3. Spatial distribution of simulated $\Delta T$ in Beijing. The daytime $\Delta T_a$ for the 2000 (a) and 2010 (b) urbanization conditions, and the nighttime $\Delta T_s$ for the 2000 (c) and 2010 (d) urbanization conditions. The (e)–(h) are same as (a)–(d) but for $\Delta T_s$. The diurnal value was calculated by averaging from 07:00 to 18:00 and the nocturnal value was averaged from 19:00 to 06:00 over June–August. The dashed black lines represent the urban areas and only the changes passed the significance test ($p < 0.05$) are included.](Image)
The correlations between temperature and background temperature showed statistically positive significance ($r \geq 0.270$, $p < 0.01$) for both 2000 and 2010 conditions (figure 5). It indicates that the UHI effect is controlled by the summer air temperature in Beijing. Furthermore, the sensitivity of T-UHI was enhanced by the urban extension. The daytime sensitivity of $T−\Delta T_s$ increased from 0.0207 °C°C$−1$ in 2000 to 0.0569 °C°C$−1$ in 2010 over the urban areas, whereas the nighttime sensitivity of $T−\Delta T_s$ increased from 0.0715 °C°C$−1$ in 2000 to 0.0995 °C°C$−1$ in 2010. Those increases suggest that urban expansion may raise the contribution of the UHI effect on the total warming and impose more serious heat stress on urban environments. Similarly, the sensitivity of $T−\Delta T_s$ also increased from 2000 to 2010, especially in the daytime, which is consistent with the finding that the relationship between impervious surface and $T_s$ varies greatly with the background temperature (He et al 2019). In addition, the differences in the mean daytime $\Delta T$ between the HW and ND periods predicted using the LRM were 101%–108% of that simulated using the WRF model (figure 5). However, it was only 44.3%–63.8% in terms of nighttime. Such a phenomenon may be attributed to the average wind speed difference, which was slightly higher during heatwaves than other normal days (figure S4). Then the stronger wind speeds may strengthen the magnitude of the surface heat flux over urban areas and thus imposed positive feedbacks to the UHI effect (Li and Bou-Zeid 2013). Another reason could be the lag of accumulated heat storage in hot days, which increases the heat release and UHI effect at nighttime during subsequent days (Zhao et al 2018b). Our results indicate that the strong UHI effect in urbanized areas during heatwaves is mainly associated with the positive sensitivity of $T−\Delta T_s$ or $T−\Delta T_{a}$. 

3.2. The sensitivity of UHI effect to background temperature

Figure 4 shows the mean $\Delta T_s$ for the 10 districts during the ‘HW’ and ‘ND’ periods. Consistent with the results reported above, the HW periods displayed stronger UHI effect than ND periods. The strongest UHI effect occurred in the center of Beijing (the CC area), which had the highest density of population, with the nighttime $\Delta T_\text{s}$ increasing from 1.19 °C (ND) to 1.82 °C (HW) in 2000 and from 1.56 °C (ND) to 2.25 °C (HW) in 2010, and the daytime $\Delta T_\text{s}$ increasing from 0.61 °C (ND) to 0.68 °C (HW) in 2000 and from 0.84 °C (ND) to 0.99 °C (HW) in 2010. The remaining areas with strong UHI effect followed by CY, HD and FT, which had the three largest population (more than 3 million) among the districts of Beijing. A weak UHI phenomenon was displayed in the suburban areas and less affected by heatwaves in the ‘Urban_2000’ experiment. However, the gap of the UHI effect between the urban and suburban areas was narrowed in both the ‘HW’ and ‘ND’ periods after the intensive urban expansion in ‘Urban_2010’. In addition, the nighttime UHI effect was more enhanced than the daytime during heatwaves, raising greater concern of high risk of heat-related mortality during hot summer nights (Laaidi et al 2012).
On the pixel scale (figure 6), the sensitivity of $T-\Delta T_a$ in the daytime was weak (approximately 0.018–0.034 °C °C$^{-1}$) in the urban areas in 2000, but it increased to 0.037–0.075 °C °C$^{-1}$ in 2010 over the same region. The sensitivity of $T-\Delta T_a$ at nighttime was higher than that in daytime, which increased from 0.041–0.119 °C °C$^{-1}$ in 2000 to 0.058–0.148 °C °C$^{-1}$ in 2010. The boundary of the areas with high sensitivity at nighttime generally matched the urban boundary. This may be because the heat released to the air from the urban surface was the major contributor to the increased temperature at nighttime. The CC area, which had nearly completed the urbanization process before 2000, still experienced an enhancement of the sensitivity because of the peripheral urban expansion. Most plain areas located in downwind of urban areas showed a positive but weak sensitivity, which displayed slight warming in the ‘Urban_2010’ (figure 3). For the surface temperature, the spatial pattern of the sensitivity of $T-\Delta T_s$ was similar to that of the artificial surface (figure 6). It indicates that urban expansion has less influence on the sensitivity of $T-\Delta T_s$ than $T-\Delta T_a$. The above results underscore the substantial differences between the sensitivity of $T-\Delta T_a$ and $T-\Delta T_s$ in their responses to urban expansion. Many studies use satellite-based surface temperature ($T_s$) data in the investigation of UHI effect due to the lack of air temperature ($T_a$) data with high spatial resolution. However, as heat stress is more related to $T_a$ than $T_s$ in summer, these studies may underestimate the nighttime heat risk caused by urban expansion and heatwaves.

3.3. Causes of the T-UHI sensitivity changes induced by urban expansion

The calculated sensitivity of $T-\Delta T_a$ showed strong agreement with the WRF modeled sensitivity (figure 7).
We found that the relative contributions of the five biophysical factors to the sensitivity of $T-\Delta T_s$ showed an apparent difference between 2000 and 2010. In both ‘Urban_2000’ and ‘Urban_2010’ experiments, the positive contribution of $\Delta LE$ was the dominant reason for the overall positive sensitivity of $T-\Delta T_s$ although the effect was offset by the negative contribution of $\Delta H$ (figure 7 and S5). This finding indicates that the difference of the evaporative fraction (=LE/(LE + $H$)) in response to increased background temperature between urban and cropland areas controls the T-UHI variance. In cropland, the land surface is mainly covered by plants and is usually water-sufficient with considerable irrigation, enabling it to have enough ability to increase the evapotranspiration in an environment with high temperature. Therefore, the energy balance over the cropland surface tends to enhance the LE rather than the $H$ to alleviate the high heat stress. In contrast, the urban areas with a high fraction of artificial surface are more likely to decrease the evaporative fraction (Bateni and Entekhabi 2012). Meanwhile, the difference in the increase of $H$ was considerably lower than the decrease of LE with urban expansion. It resulted in increases in the differences in available surface energy ($\Delta H + \Delta LE$), contributed the sensitivity of 0.038 °C °C$^{-1}$ in 2000 to 0.088 °C °C$^{-1}$ in 2010. This change made the largest contribution (123.58%) to the increase in $T-\Delta T_s$ sensitivity.

The $\Delta SW_{net}$ contributed 0.092 °C °C$^{-1}$ in 2000 and only 0.051 °C °C$^{-1}$ in 2010 to the sensitivity of $T-\Delta T_s$ (figure 7), but the $\Delta LW_{down}$ showed an insignificant correlation with $T_s$ ($r \leq 0.116$, $p \geq 0.17$, figure S6). Because the $\Delta SW_{net}$ is highly sensitive to $\Delta SW_{down}$ due to the relatively low albedo of urban canopy, the result of $\Delta SW_{net}$ led to less confidence in the change in the sensitivity of $T-\Delta T_s$. The sensitivity change contributed by the $\Delta LW_{down}$ was small as it was neither closely related to urban expansion nor highly sensitive to small temperature change (figure S7). The last contributor was the change in $\Delta G$ which was negative in the daytime (heat storage in the surface) and positive at nighttime (heat release from the surface). $\Delta G$ change caused a slight reduction in the sensitivity of $T-\Delta T_s$ from 2000 to 2010 because of the increased heat absorption and storage during daytime (figure S5). It is worth to note that our method of calculating the contributions of the biophysical factors is still unable to reveal the differences between daytime and nighttime. However, the dominant contributors to the UHI effect are different between daytime and nighttime. Figure S5 shows that $\Delta LE$ controlled the daytime UHI effect whereas $\Delta G$ (change in stored heat) was the main contributor to the nighttime UHI effect. As a result, there was a larger increase in the daytime sensitivity of $T-\Delta T_s$ than the nighttime from 2000 to 2010 (figure 5(b)).

4. Conclusions and implications
We employed the WRF model to investigate the UHI effect in response to urban expansion and heatwaves during the summer in Beijing. As expected, the UHI effect described by $\Delta T_s$ or $\Delta T_b$ increased dramatically in ten districts due to urban expansion and heatwaves. Moreover, we found a positive relationship between the UHI effect and background temperature, which resulted in an enhanced UHI effect in heatwaves. We examined this relationship as the sensitivity of $T-\Delta T_s$ and $T-\Delta T_b$, finding the spatial pattern of the sensitivity was similar to that of the artificial surface over urban and suburban areas. The sensitivity of $T-\Delta T_s$ increased
from 0.0207 °C°C−1 in 2000 to 0.0569 °C°C−1 in 2010 in the daytime and from 0.0715 °C°C−1 in 2000 to 0.0995 °C°C−1 in 2010 at nighttime in Beijing as a result of urban expansion. Such changes in sensitivity can clearly explain the changes in UHI effect associated with urban expansion and heatwaves. Our investigation of the biophysical factors revealed that the changes in the sensitivity of T−ΔT were mainly due to the increase in the available energy difference (ΔH + ΔLE). With increasing temperature, the surface energy balance impeded the cooling contribution of LE but enhanced the heat storage during daytime and the heat release during nighttime in urban canopy.

The sensitivity of T-UHI is an indicator to provide the valuable information about the change of the UHI effect under different background temperature for urban planning. A positive sensitivity of T-UHI indicates a higher UHI effect in a warming environment over an urbanized region, while an enhanced sensitivity resulted from urban expansion means a larger contribution of the UHI effect to the total warming. Those extra warmings aggravate the heat stress and harm the urban ecosystem and economies (Ma et al 2015, Estrada et al 2017, Battles and Kolbe 2019). In this situation, the city governments, such as Beijing, should pay more attention to the additive UHI effect and continued background temperature warming in urban planning.

The attribution analysis of biophysical factors offers insight into how mitigation strategies of the UHI effect can impact on the sensitivity of T-UHI. We found the largest contribution to the enhanced T-UHI sensitivity was from the deficit of evaporation over urban areas. Thus, the measures aiming to increase the evaporation, including cover improvement of green lands and water bodies (Ellison et al 2017) and employment of green roofs (Santamouris 2014), can depress the sensitivity. Another widely used strategy to mitigate the UHI effect is the usage of cool roofs with high albedo, which can greatly reduce the SW net (Vahmani et al 2016, Macintyre and Heaviside 2019), thus possibly producing a negative contribution to the sensitivity. A novel adaptation strategy is to use the lightweight urban materials, with the purposes to decrease the heat release from urban canopy in nighttime (Krayenhoff et al 2018). This may reduce the sensitivity of T-UHI at nighttime.

In conclusion, our findings show that the positive sensitivity of T-UHI which resulted in the obviously increased UHI effect during heatwaves was enhanced by urban expansion, exacerbating heat risks over the urban areas of Beijing. However, the sensitivity of T-UHI could be various in different climate zones. Meanwhile, the regional climate context may shift dramatically with future global warming (Fitzpatrick and Dunn 2019), which may change the local sensitivity of T-UHI for the city. To better understand the impacts of urbanization and global warming on the urban thermal environment, additional work should aim to examine the variations of the sensitivity of T-UHI across a wide range of cities with geographic and climate contexts.

Acknowledgments

The work was supported by National Key R&D Program of China (2017YFC0505702), the National Natural Science Foundation of China (41741017, 41601556), and the Chinese Academy of Sciences (QYZDB-SSW-DQC034). Daily meteorological observation data are collected from the China Meteorological Data Service Center (http://data.cma.cn) and the Beijing Urban Ecosystem Research Station (http://bjurban.rcees.ac.cn). The MODIS land surface temperature dataset is provided by NASA Earthdata Services (https://urs.earthdata.nasa.gov). The model outputs used in this study are available at https://drive.google.com/open?id=1Kq5SXM4ucVUrqhmdrW5CazkJHpi8jiuW. We would like to thank the anonymous reviewers for their valuable comments and suggestions.

ORCID iDs

Zhen Gao @ https://orcid.org/0000-0002-1437-3575

References

Arnfield AJ 2003 Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island Int. J. Climatol. 23 1–26
Bateni SM and Entekhabi D 2012 Relative efficiency of land surface energy balance components Water Resour. Res. 48 11357
Battles A C and Kolbe J 2019 Miami heat: urban heat islands influence the thermal suitability of habitats for ectotherms Glob. Change Biol. 25 562–76
Cao Q, Yu D, Georgescu M, Wu J and Wang W 2018 Impacts of future urban expansion on summer climate and heat-related human health in eastern China Environ. Int. 112 134–46
Cao Q, Yu D, Georgescu M and Wu J 2016 Impacts of urbanization on summer climate in China: an assessment with coupled land-atmospheric modeling J. Geophys. Res. Atmos. 121 10505–21
Chapman S, Watson J E M, Salazar A, Thatcher M and McAlpine C A 2017 The impact of urbanization and climate change on urban temperatures: a systematic review Landscape Ecol. 32 1921–35
Chen F and Dudhia J 2001 Coupling an advanced land surface–hydrology model with the penn state–NCAR MM5 modeling system: I. Model implementation and sensitivity Mon. Wea. Rev. 129 569–85
Coutris AM, Daly E, Beringer J and Tapper N J 2013 Assessing practical measures to reduce urban heat: green and cool roofs Build. Environ. 70 266–76
Cui Y, Yan D, Hong T and Ma J 2017 Temporal and spatial characteristics of the urban heat island in Beijing and the impact on building design and energy performance Energy 130 286–97
Dee D P et al 2011 The ERA-Interim reanalysis: configuration and performance of the data assimilation system Q. J. R. Meteorol. Soc. 137 553–97
Duveiller G, Hooker J and Cescatti A 2018 The mark of vegetation change on Earth’s surface energy balance Nat. Commun. 9 679
Zhang D L, Shou Y X and Dickerson R R 2009 Upstream urbanization exacerbates urban heat island effects Geophy. Res. Lett. 36 41082
Zhang K, Wang K, Shen C and Da L 2010 Temporal and spatial characteristics of the urban heat island during rapid urbanization in Shanghai, China Environ. Monit. Assess. 169 101–12
Zhang Z X et al 2014 A 2010 Update of national land Use/Cover database of China at 1:100000 scale using medium spatial resolution satellite images Remote Sens. Environ. 149 142–54
Zhao G et al 2018a Evapotranspiration-dominated biogeophysical warming effect of urbanization in the Beijing–Tianjin–Hebei region, China Clim. Dyn. 52 1231–45
Zhao L, Lee X, Smith R B and Oleson K 2014 Strong contributions of local background climate to urban heat islands Nature 511 216–9
Zhao L et al 2018b Interactions between urban heat islands and heat waves Environ. Res. Lett. 13 034003
Zhao Z Q, He B J, Li L G, Wang H B and Darko A 2017 Profile and concentric zonal analysis of relationships between land use/land cover and land surface temperature: case study of Shenyang, China Energy Build. 155 282–95
Zhou D, Zhao S, Zhang L, Sun G and Liu Y 2015 The footprint of urban heat island effect in China Sci. Rep. 5 11160
Zhou L et al 2004 Evidence for a significant urbanization effect on climate in China Proc. Natl Acad. of Sci. 101 9540–4