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Abstract

This study investigated impacts of urban forms on the future thermal environment over Beijing, the capital city of China. Beijing is experiencing remarkable urban expansion and is planned to undergo the transformation of urban forms from single-centric (compact-city) to poly-centric city (dispersed-city). Impacts of urban forms on the future thermal environment were compared and evaluated by conducting numerical experiments based on a regional atmospheric model coupled with a single-layer urban canopy model as well as future climate forcing output from a global climate model. Results show that a dispersed city is efficient in reducing mean urban heat island intensity, but produces larger thermal loading and deeper thermal feedback at the regional scale compared to a compact city. Thermal comfort over downtown areas is reduced in compact-city scenario under future climate conditions. Future climate contributes almost 80% of the additional thermal loading over urban areas, with the remaining 20% contributed by urbanization (for both the compact-city and dispersed-city scenarios). The thermal contrast between the two urban forms is dominated by the expected future climate change. This study leads to two complementary conclusions: (i) for developing assessments related to current climate comfort, urban form of the city is important; (ii) for assessing future climate change impacts, the areal coverage of the city and urbanization extent emerges to be more important than the details related to how the urbanization will evolve.

1. Introduction

Urbanization, characterized by the conversion of natural (e.g., vegetation) to artificial surfaces (with contrasting physical and thermal properties, e.g., surface albedo, heat capacity) and boom in urban population, contributes to the deterioration of urban thermal environment. Urbanization impacts transcend far beyond its physical boundary and could also affect severe weather (Niyogi *et al* 2006, 2011), hydrological cycles (e.g., Shepherd 2005, Yang *et al* 2013a, 2013b), biodiversity (Seto *et al* 2012), air quality (Jacobson *et al* 2015), energy consumption (Martilli 2014) and human health (Hondula *et al* 2014).

Transformation of urban forms is regarded as an effective tool for alleviating negative impacts of urbanization on the thermal environment (Landsberg 1981, Oke 1984, Scherer *et al* 1999, Stone and Rodgers 2001, Hathway and Sharples 2012, Schwarz *et al* 2013). Stone *et al* (2010) investigated correlations between urban forms and the frequency of extreme heat events over selected US cities, and concluded that increasing rates for extreme heat events in sprawling cities is twice as large as that in compact cities.

However, Adachi *et al* (2014) found that a compact city has the potential to moderate the mean urban heat island effect (i.e. urban–rural contrast of air temperature) over the entire Tokyo metropolitan area, but might further increase total thermal loadings over downtown Tokyo. Considering that changes in urban structures are varied in cities and regions, the effectiveness of urban forms in mitigating heat-related risks also varies (Frolking *et al* 2013). For cities in developing countries, transformation of urban forms is commonly associated with the decrease of surrounding rural/vegetated surfaces (outward expansion); while it may not be the case for most cities in developed countries where available rural spaces are already limited. Cities in developed countries tend to increase vertically and in capacities within existing urban frames (upward expansion) (Adachi *et al* 2014). The expansion of urban land cover globally is projected to be accelerated into 2050s, with most expansion taking place in the developing world (Angel *et al* 2011). In this study, we will focus on urban development in the Beijing metropolitan area (BMA), China.

As one of the largest mega-cities in the world, Beijing has witnessed astonishing urbanization rate in recent decades (Bureau 2012, Zhao *et al* 2015). Analysis of Landsat images from 1990 to 2005 indicates a 7-fold increase in the urban footprint of the Beijing urban region (Miao 2015). Rapid expansion of metropolitan area will continue to play a vital role in the development of Beijing metropolitan area in future. The current urban population is 16 million over the entire BMA, and this number is projected to double by 2050s (see figure S1 for more details). According to the city master plan approved by the National Council, the urban spatial structure for BMA will gradually shift from a mono-centric (compact) city to a poly-centric (dispersed) city (more details about the city master plan are available at http://zhengwu.beijing.gov.cn/ghxx/ztgh/). It is therefore an interesting opportunity to examine the impacts of the projected transformation in urban forms on regional environment (urban heat island, total thermal loading, etc). We aim to provide references regarding the potential environmental feedbacks related to urban transformation for city planners and policy makers.

Another related aim of this study is to make projections on relative contributions of urbanization and climate change to future warming over BMA under the compact versus dispersed urban forms. The historical contribution rate to regional warming has been examined in previous studies (Zhou *et al* 2004, Ren *et al* 2007). For instance, Ren *et al* (2008) derived that warming rate due to urbanization is about 0.11 °C per decade over North China (including BMA). Zhou *et al* (2004) estimated that urbanization contributed 0.05 °C per decade increase of mean near-surface temperature in southeast China. However, future projection of warming rate due to urbanization is still lacking for the BMA region.

2. Methodology

We designed two urban forms for future Beijing according to the master plan: compact-city and dispersed-city. The dispersed-city design corresponds to the poly-centric urban pattern in the master plan. For the two urban forms, we examine the future urban warming effect based on the Weather Research and Forecasting model-Advanced Research Version (WRF) coupled with an explicit urban canopy model (Chen *et al* 2011). The model was driven by downscaled future climate forcing scenarios as well as land use scenarios. We focus on a heat wave case during July 2010 over BMA. Daily Maximum air temperature attained over 40 °C for a large sample of temperature stations over BMA (see figure S2 for more details).

2.1. Projections of future urban development

We made projections on future urban coverage over BMA based on the projected increase in urban population, assuming that the total urban coverage should be at least doubled so as to accommodate the new urban inhabitants (since logistic regression model show urban population is to be doubled in 2050s). In this study, we assumed urban coverage sprawls at the expense of converting suburban/rural areas in the surroundings, instead of increasing capacities within current urban regions (e.g., shrinking green spaces, increasing heights/densities of buildings, etc), which is typical especially for city growth in developing countries.

Two contrasting urban forms were designed in this study: compact- and dispersed-city. For compact-city, additional urban coverage was distributed around the old urban core region (downtown Beijing, see figure 1), which maintained a mono-centric urban form (figure 1(c)); while for dispersed-city, the additional urban coverage was distributed onto five subregions (including Changping, Fangshan, Daxing, Tongzhou and Shunyi) surrounding the old urban core region, exhibiting a pattern of poly-centric urban form (figure 1(d)) as designed in the master plan. We note that the additional urban coverage mainly belongs to the category of high-density residential land use (see section 2.2 for numerical representations of land use in the model).

2.2. Model descriptions and configurations

Simulations in this study were conducted using the Advanced Research version of WRF, ARW V3.4 (Skamarock *et al* 2008). We configured three one-way nested model domains. The inner domain (D03), with horizontal spatial resolution of 1 km, was centered over Beijing metropolitan region (figure 1(a)). The WRF model was coupled with a Single-Layer Urban Canopy Model (SLUCM), to capture the characteristics and dynamics of heat/moisture fluxes over urban areas (Chen *et al* 2011). A three-category urban

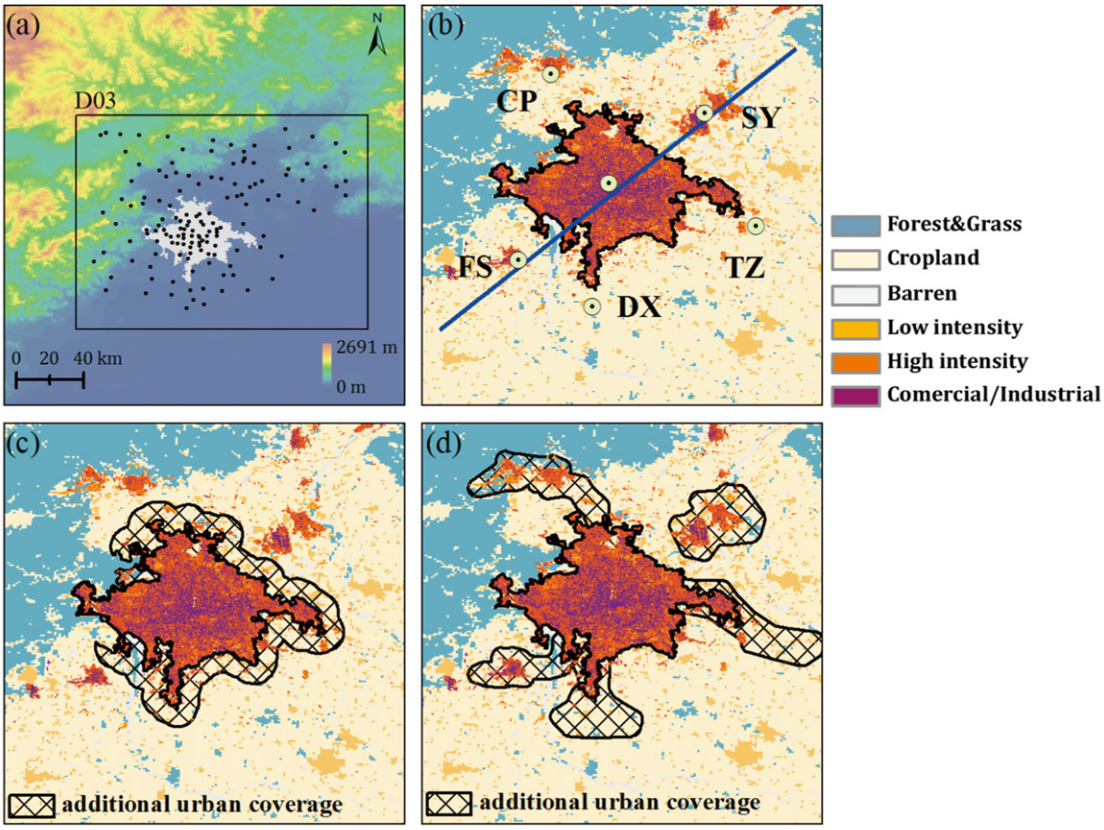

Figure 1. (a) Topographic features of Beijing metropolitan region. Elevation is shaded. Grey area represents the urban core region (i.e. downtown region). Black dots are surface meteorological stations that are used in the WRF model validation. The black box is the most inner domain of WRF simulations; (b) current land use/land cover of Beijing metropolitan region, green dots represent five sub-regions of Beijing metropolitan region, include: CP-Changping, FS-Fangshan, DX-Daxing, TZ-Tongzhou and SY-Shunyi; the black line highlights the boundary of downtown Beijing; the yellow straight line represents a cross-section though the metropolitan region; (c) land use/land cover in compact-city scenario, additional urban coverage (consists of high density urban land use) is highlighted by crosshatches; (d) same as (c) but for dispersed-city scenario.

land use (representing low-intensity residential, high-intensity residential and industrial/commercial, respectively) was incorporated into the model for better representations of surface heterogeneity over urban areas. The three-category urban land use was developed based on remote sensing images of Landsat TM5 (see Hou 2012 for more details) and has been used in previous urban climate studies (Hou *et al* 2012, Yang *et al* 2014). The default parameters in SLUCM were used in this study (see Chen *et al* 2011 for more details). Other physical options were summarized in table S1. Previous studies have extensively examined the utility of current configurations of WRF/SLUCM model over BMA (Miao *et al* 2009, 2011, Zhang *et al* 2009, Yang *et al* 2014).

Uncertainty for the simulations could originate from the initial/boundary conditions for the model (Wu *et al* 2005). We conducted three ensembles driven by different datasets, including JRA-55, GFS-FNL and ERA-interim (see table S2). We validated the simulation results against corresponding 2 m air temperature observations. The mean bias of simulated 2 m air temperature is −0.02 °C (with the standard deviation of 2.4 °C) with ERA-interim dataset, compared to −1.6 ± 2.7 °C with JRA-55, and −0.24 ± 2.6 °C with FNL (see figure S3 for more details). In addition, simulation results with ERA-interim exhibited better spatial distribution of temperature bias than the other two datasets (see figure S4). Spatial-average temperature shows smallest bias with ERA-interim data (see figure S5). Accordingly, we chose ERA-interim as initial and boundary conditions for WRF/SLUCM simulations in the following analyses. Simulation period of the modeling system covers the entire period of heat wave case (from 0000 UTC 1 July to 0000 UTC 7 July 2010). Results for the peak heat wave period (4–6 July 2010) were analyzed and presented, placing 00 UTC 1 July to 00 UTC 4 July as the spin-up period. Time interval for model output was one hour, so as to match up the frequency of observations.

2.3. Experiment designs

We analyzed changes in thermal environment under both future climate change at 2050s and urban development (as represented by changes in urban forms and size). Climate forcing corresponding to 2050s was provided based on the Community Earth System Model (CESM, http://www2.cesm.ucar.edu/)

Table 1. Experimental design.

No.	Experiment name	Urban scenarios	Initial/boundary conditions
R1	ctl_curr	current urban	ERA-interim in 2010
R2	com_curr	compact-city	ERA-interim in 2010
R3	dis_curr	dispersed-city	ERA-interim in 2010
R4	ctl_fut	current urban	CESM in 2050s
R5	com_fut	compact-city	CESM in 2050s
R6	dis_fut	dispersed-city	CESM in 2050s

under one future emission scenario which is Representative Concentration Pathways 8.5 (RCP 8.5) (Riahi *et al* 2011). Climate forcing from CESM was further 'downscaled' into a finer spatial and temporal resolution based on the pseudo-global warming downscaling (PGW-DS) approach (see Kawase *et al* 2009, Lauer *et al* 2013 for more details about the downscaling approach). The downscaled forcing was then used to provide initial/boundary conditions for WRF/SLUCM model under future climate scenarios, while ERA-interim reanalysis data was used for current climate scenarios.

In total, an ensemble of two climate forcings and three urban scenarios (current urban coverage, compact- and dispersed-city) were examined, resulting in six numerical experiments (table 1). We focus especially on the contrasting behaviors between two urban scenarios under future climate conditions, and the simulation results based on ctl_fut, com_fut and dis_fut runs will be analyzed and presented in the following section. Simulation results from other numerical experiments (e.g., com_curr, dis_curr) will be mainly used to determine relative contributions of future climate and urban forms to the changes in thermal environment over BMA.

3. Results

3.1. Contrasting impacts on thermal environment

We analyzed contrasting impacts on thermal environment mainly from three perspectives: (i) thermal contrast between urban and surrounding rural regions that is the urban heat island intensity, (ii) total thermal loading (as represented by air temperature and heat stress index) at downtown and broader regional scale, and (iii) the vertical extent of the thermal perturbation.

3.1.1. Urban heat island intensity (UHII)

We define UHII as the difference between 2 m air temperature averaged over urban region and that over surrounding rural region (with a similar spatial scale with urban region) (Oke 1982). Figure 2(a) shows time series of UHII for three future scenarios (ctl_fut, com_fut and dis_fut). Relative differences between two future urban scenarios (R5 and R6) and current urban scenario (R4) are shown in figure 2(b). The UHII values range from 1 °C to 4 °C for the three simulations. There is a notable contrast between the simulations close to sunrise and sunset. The maximum UHII (about 4 °C) under the heat-wave period is comparable but relatively larger in this study compared to previous studies (with a range of 2 ∼ 3 °C, not specifically focus on heat-wave periods) (Ryu and Baik 2012, Zhou *et al* 2013). The increased UHII under the heat-wave period could possibly be attributed to the synergistic effects between heat wave and urban heat island as discussed for instance in Li *et al* [2015].

The thermal contrast evolves quite differently for the two urban forms. Compact-city scenario further enhances UHII by 0.1 °C (averaged over the peak heat wave period) compared to current urban scenario; while UHII is reduced by 0.4 °C on average in dispersed-city scenario. The anomalies of UHII induced by two different urban forms (with respect to the control scenario) are statistically different at the significance level of 1% based on the student's t-test. Contrast in UHI shows that dispersed-city is more efficient in moderating summertime heat island phenomena than compact-city. We note that both the urban forms are spread over an area of total urban coverage twice as large as the current urban scenario. The thermal contrast between urban and surrounding rural regions could be directly related to the transformations of surrounding rural areas (mainly in the forms of crops, grassland and other vegetated surfaces) into urban coverages (paved road, roofs, etc) under future urban development.

3.1.2. Thermal loading at downtown and at the regional scale

We evaluated impacts of urban forms on thermal loading as represented by both 2 m air temperature and heat stress index, expecting to provide a broader implication for meteorological perspectives as well as human health. The heat stress index is based on a measure of apparent temperature that reflects both temperature and humidity (Steadman 1984), and takes the form of:

$$A = -1.3 + 0.92T + 2.2e \quad (1)$$

where T is 2 m air temperature (°C) and e is water vapor pressure (kPa) at 2 m. Both T and e are simulated by the WRF/SLUCM modeling system. Temporal average (over the peak wave period of 4th–6th July 2010) air temperature and heat stress index are averaged at different spatial scales.

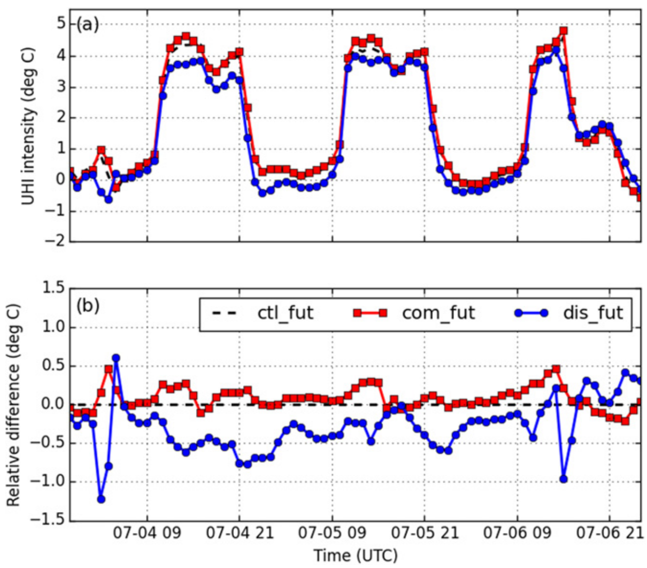

Figure 2. Time series of (a) UHI intensity (°C) for control, compact-city and dispersed-city scenarios under the 2050s climate and (b) difference of UHI intensity between compact-city and control scenario (com_fut minus ctl_fut) as well as dispersed-city and control scenario (dis_fut minus ctl_fut).

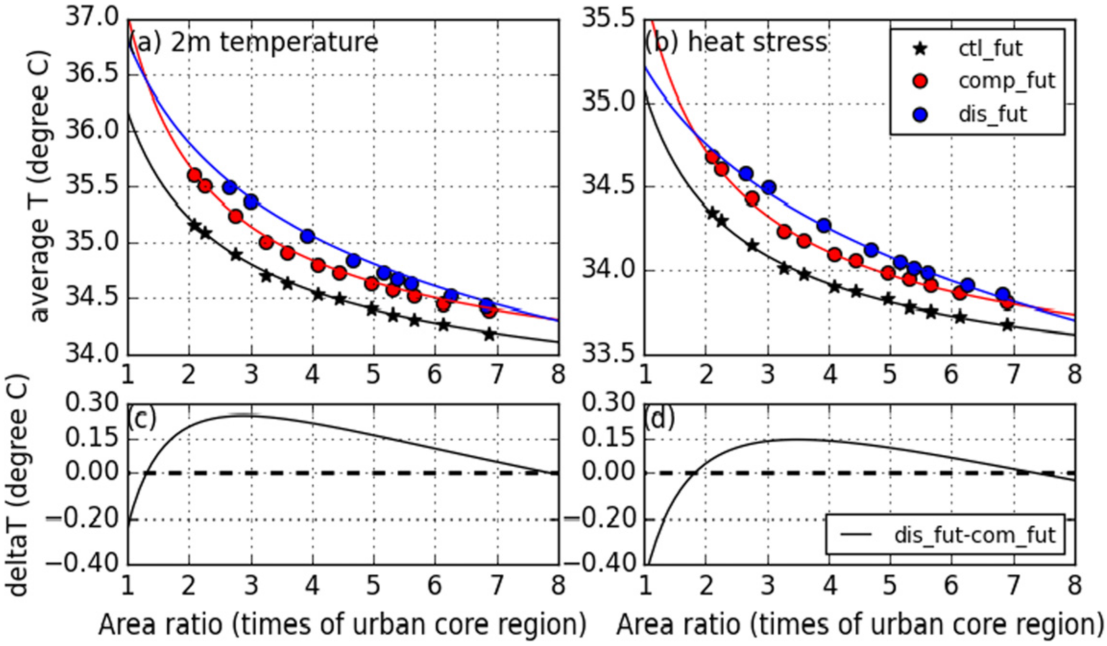

Figure 3. Horizontal spatially averaged (a) 2 m air temperature and (b) heat stress index over and beyond the extent of urban coverage under future climate condition. *X*-axis is the horizontal extent. The differences between compact- and dispersed-city scenario are shown in (c) and (d) for 2 m temperature and heat stress index, respectively. Dots are based on results from WRF simulations. Lines shown in (a) and (b) are fitted using power-law functions. The legend of (a) is the same as (b), and also the legend of (c) is the same as (d).

Both changes of air temperature and heat stress index fit a quadratic function of spatial extent (figure 3). In this study, the spatial extent is represented by ratios of the buffering area surrounding urban coverage to that of original urban core region (downtown region, see figure 1(b)). For instance, area ratio equal to one means spatial scale covering downtown area only, while area ratio equal to 2 means twice as large as downtown coverage (figures 1(c) and (d)) (see also Zhou *et al* 2015).

Both air temperature and heat stress index decay quadratically from downtown area towards surrounding rural area (figures 3(a) and (b)). The decaying trend of thermal loading has been recorded in previous

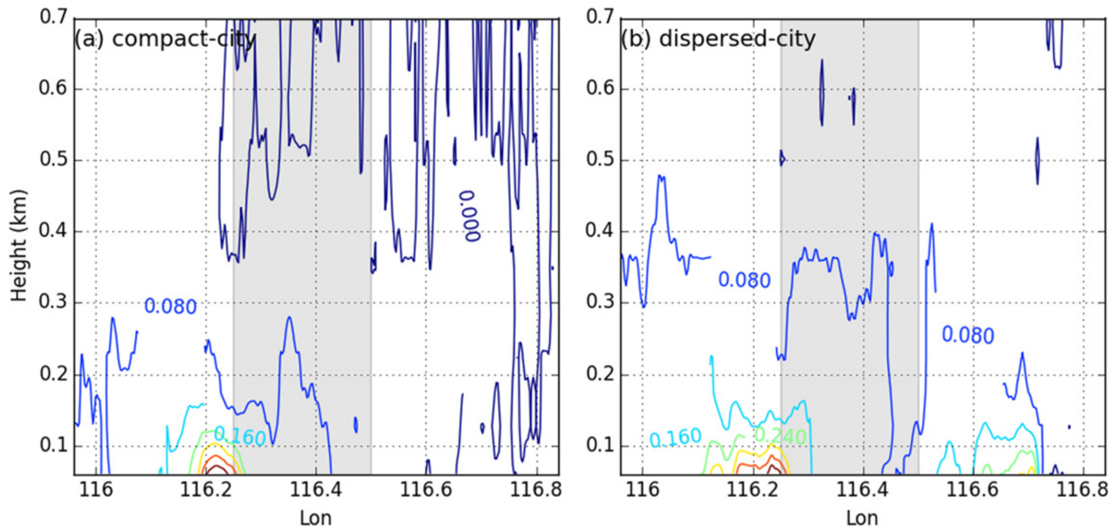

Figure 4. Differences of potential temperature profiles along the cross section (shown as the yellow straight line in figure 1(b)): (a) compact-city (com_fut minus ctl_fut) (b) dispersed-city (dis_fut minus ctl_fut). The downtown area is shaded in grey.

studies based on either *in situ* or remote sensing observations (Jin *et al* 2005, Zhou *et al* 2015). In this study, we are particularly interested in the contrasting spatial decaying pattern between two urban forms of compact- and dispersed-city. Because of the increased urban area, it is expected that both compact- and dispersed-city produce larger thermal loading at all spatial scales than current urban scenario. However, the contrast between compact- and dispersed-city scenarios is also noticeable even though both scenarios are over twice the urban coverage compared to the current urban. Dispersed city produces a larger regional warming effect (beyond downtown area, corresponding to area ratios larger than 1), with 2 m air temperature and heat stress index higher by 0.25 °C and 0.15 °C than compact-city scenario, respectively. The contrast between the two scenarios gradually decays with the increased spatial extent (figures 3(b) and (d)). There is no noticeable difference between two urban forms at spatial scales of 7 ∼ 8 times of downtown area, which indicates that different perturbations on thermal loading induced by urban forms are confined within certain spatial scale (around 40 km way from the city center).

Unlike the impacts on thermal loading at spatial scales beyond downtown region, compact city produce a larger warming effect than dispersed city, with air temperature and heat stress index larger by 0.2 °C and 0.4 °C as compared to the dispersed city respectively (figures 3(c) and (d)). Larger thermal loading in the downtown area indicate deteriorated urban environment for city inhabitants with higher potential of health-related risks under future climate (Hondula *et al* 2014). We note that heat stress index will exceed 35 °C in downtown Beijing for all three future scenarios. The minimum spatial-average heat stress index is above 33 °C, which is even larger than maximum heat stress index under current climate conditions (see figure S6 for more details). Sherwood and Huber (2010) put forth that any prolonged exposure beyond 35 °C could induce hyperthermia in humans and other mammals due to the impossibility of dissipation of metabolic heat. The total amount of emergency department visits are 10% more in Beijing during the 2010 heat wave period than the same historical period (Liu *et al* 2014).

3.1.3. Thermal perturbation in vertical extent

Figure 4 shows the relative differences of potential temperature profiles (averaged over the entire period of 4–6 July 2010) for compact-city/dispersed-city scenarios to a control scenario. The vertical impact decreases at higher altitudes for both the urban forms. However, the vertical extents of thermal impact are contrasted in two scenarios. A dispersed city produces a deeper perturbation than compact city. More specific, the potential temperature difference reaches 0.08 °C at the height of 250 m for the compact-city scenario, while the same perturbation as 0.08 °C was pushed to a higher altitude of around 400 m for the dispersed-city scenario. The perturbation on potential temperature is not confined within vertical extents over the additional urban coverage for compact- and dispersed-city scenarios, but could extend to a larger horizontal extent covering the entire metropolitan region.

The deeper thermal influence noted in the vertical profile of potential temperature in dispersed-city scenario highlights a higher potential for increased instability leading to higher turbulent kinetic energy and planetary boundary layer height, which might provide favorable conditions for vertical mixing of urban pollutants and influence assessment of air quality over urban regions (Georgescu 2015).

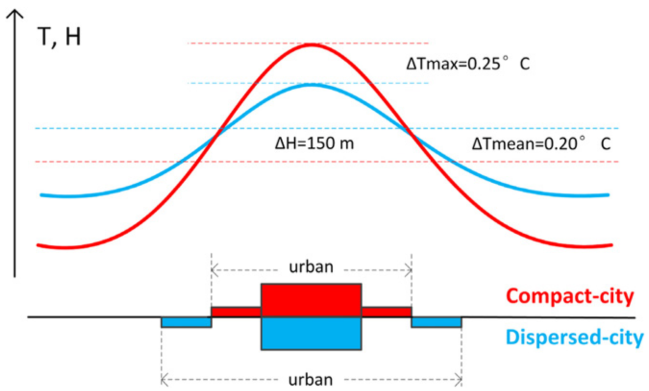

Figure 5. Schematic contrasts of the impacts on thermal environment between compact- and dispersed-city scenarios. Horizontal dashed lines represent maximum temperature for compact and dispersed-city, and mean temperature for dispersed- and compact-city, respectively. Red: compact-city and blue: dispersed-city.

Table 2. Temperature increase and relative contributions. Percentages are shown in parentheses. The temperature is evaluated over downtown area.

Urban scenarios	Total increase (°C)	Attributable to climate (°C)	Attributable to urbanization (°C)	Due to interactions (°C)
compact-city	2.98	2.44 (82%)	0.5 (17%)	0.04 (1%)
dispersed-city	2.89	2.44 (85%)	0.4 (13%)	0.07 (2%)

The contrasting impacts for the two urban forms are illustrated in figure 5. Both compact- and dispersed-city scenario increase thermal loading under future climate, but are contrasted by the magnitudes and spatial extents. The increased thermal loading is more concentrated over the urban core region for the compact-city scenario, while for the dispersed-city scenario the increased thermal loadings are relatively spread out over the region. The contrasting impacts of urban forms on thermal environment are not restricted within downtown area or urban coverage, but extend into a larger spatial scale both horizontally and vertically beyond the urban landscape.

3.2. Relative contributions of future climate and urbanization to temperature increase

To extract the relative contributions of future climate (F_{climate}) and urbanization ($F_{\text{urbanization}}$) a factor separation analysis (Stein and Alpert 1993) was undertaken. The analysis considers the following equations:

$$F_{\text{climate}} = R_4 - R_1 \quad (2)$$

$$\text{compact\_city:} \quad F_{\text{urbanization}} = R_2 - R_1 \quad (3)$$

$$F_{\text{interactions}} = (R_5 - R_2) - (R_4 - R_1) \quad (4)$$

$$\text{dispersed\_city:} \quad F_{\text{urbanization}} = R_3 - R_1 \quad (5)$$

$$F_{\text{interactions}} = (R_6 - R_3) - (R_4 - R_1) \quad (6)$$

where R_1 to R_6 correspond to different numerical experiments as listed in table 1.

Urbanization contributes to the temperature increase by 0.5 °C for compact-city scenario ($R_2 - R_1$) and 0.4 °C for dispersed-city scenario ($R_3 - R_1$), at the rates of 0.1 ~ 0.13 °C per decade. Future climate contributes 2.44 °C of temperature increase, taking up more than 80% of the total increased thermal loading (see table 2). The projected warming rate due to urbanization is comparable to historical evaluation (0.11 °C per decade) over BMA, but relative contribution is smaller than historical estimation (which is 40 ~ 61% during 1981–2000 as estimated in previous studies as Ren *et al* (2007, 2008)). From urban climate modeling perspective, the difference between compact- and dispersed-city scenarios is thus relatively a smaller consideration compared to the overwhelming impact of future climate on temperature increase, although thermal comfort over downtown Beijing is slightly better in dispersed-city scenario than compact-city scenario.

4. Summary and discussions

In this study, we compared the contrasting impacts of urban forms on thermal environment under future climate conditions taking the Beijing metropolitan region as an example. Future urban forms are represented by compact- and dispersed-city scenarios, with the latter being specifically designed as a future city form by the local government. Our analyses show that dispersed city is effective in alleviating mean urban heat island intensity, as well as producing a smaller thermal loading over downtown region compared to compact-city scenario. However, the regional warming effect is more significant in the dispersed-city scenario, due to the conversion of surrounding vegetated surface to urban coverage. For the compact-city scenario, the additional urban coverage is only at the expense of sub-urban area that surrounds the downtown region. The larger regional warming in the dispersed-city scenario might also potentially increase the depth of vertical circulation by producing a deeper perturbation on vertical temperature profile under future climate over the domain.

Contrasts between compact- and dispersed-city scenarios indicate that no one scenario outperforms the other by all means. The 'superiority' of urban forms is conditioned on perspectives in evaluation. For instance, the dispersed-city scenario might be effective in moderating the urban heat island or heat stress increase over the downtown region, but this scenario might increase the potential of more frequent warm-season thunderstorms over urban areas, which is typically not considered by city dwellers and urban planners (e.g., Yang *et al* 2014). In addition, the warming effect might have broader implications beyond urban climate and human comfort (Grimm *et al* 2008), for instance, the phenology of vegetation surrounding urban areas could be significantly disturbed by the urban heat island effect (Zhang *et al* 2004, Zhou *et al* 2014), impact on biodiversity and carbon pools (Seto *et al* 2012), and regional air quality (Jacobson *et al* 2015). The thermal impact beyond urban coverage is also known as urban footprint (Zhang *et al* 2004). More recently, Zhou *et al* (2015) conducted a regional analysis of the urban footprint for 32 major cities in China, which included the Beijing metropolitan region. Our study finds that the thermal contrast between different urban forms diminishes at the spatial extent with the entire area being 7 ~ 8 times of the urban core region. That is, the urban thermal footprint may influence about 7 ~ 8 times the size of the urban area (around 40 km away from the city center). Schmid and Niyogi [2013] discussed the threshold of city size for urban modification on thunderstorms, and found the magnitude of precipitation modification increased linearly with the radius of a city up to 20 km, where it became more consistent with increasing city size.

Cities evolve both in size and forms by transforming surrounding rural or vegetated areas. This is a typical development scenario for cities in developing countries. As such, findings from our study directly apply for city planners in developing countries. Results also show that future climate warming contributes to more than 80% of total thermal loading over BMA, with the rest effect from urbanization. Thus results from this study indicate that the impact of regional warming or climate change is larger than the impact of urban extent for urban thermal loading, followed by urban form as the third important factor.

There are no 'one-size-fits-all' type solutions for maintaining sustainable cities (Georgescu *et al* 2015). Comprehensive mitigation tools should be examined in conjunction with urban forms to enhance the adaptability of cities to potential heat-related risks under the context of global warming. Potential mitigation tools include: reducing surface albedo through configuration of green/white roofs (Georgescu *et al* 2014, Li *et al* 2014), expanding green vegetation coverage within downtown region (Zhang *et al* 2009), and also reconstructing the structures of industries and energy consumption.

The issue being addressed has multiple scales and indeed it is possible to use multiple approaches to investigate the interactions. Every study and approach has certain limitations, as are also inherent to our study. For example, anthropogenic heat is an important but an uncertain component of the urban energy budget. In the WRF/SLUCM modeling systems used in this study, anthropogenic heat is represented by characteristic diurnal cycles that are directly linked to urban land use categories (Chen *et al* 2011). Anthropogenic heat is generally contributed by three main sectors: building, human metabolism and traffic (Sailor 2011, Sailor *et al* 2015). Current consideration in anthropogenic heat underestimates contributions from traffic sector over cities with different urban forms. For instance, in dispersed-city scenario, anthropogenic heat from traffic sectors should be most influenced by frequent commute between new residential centers and downtown region. Emissions from transportation in dispersed-city scenario would further enhance regional thermal loading as identified in this study. For compact-city scenario, variation of anthropogenic heat depends on outside air temperature, which is determined by the positive feedback between temperature and air-conditioning energy demand (Kikegawa *et al* 2003, Gago *et al* 2013). We note that total thermal loading over downtown region should be even larger in compact-city scenario. Even though we used the default configurations related to anthropogenic heat in all the simulations, the contrast between two urban forms should not change but may intensify to some extent when dynamic (i.e. considering traffic flow and air conditioning) anthropogenic heat components are considered. The relative contributions to temperature increase from the urbanization side should take a larger portion than 20%, which highlights the importance of extra mitigations tools in moderating future thermal risks. Future studies need to come up with comprehensive urban scenarios with both changes in urban coverage and socioeconomic variations (such as changes in energy structures, green planning, etc) considered.

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