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RESEARCH ARTICLE

Urban expansion and local land-cover change both significantly contribute to urban warming, but their relative importance changes over time

Xiaofang Hu · Weiqi Zhou · Yuguo Qian · Wenjuan Yu

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Abstract
Context The urban heat island (UHI) affects both biogeochemical cycles and human society. Previous studies of UHI indicate urban expansion and local land-cover change can lead to higher temperatures in cities compared to the adjacent countryside. Few studies have examined the joint effects of city- and local-scale factors on urban warming, and their relative importance.
Objectives We examined the overall impact of urbanization on urban warming from 1983 to 2011 in Beijing, investigated how city size and the proportion of local developed land jointly influenced the air temperature, and quantified their relative importance over time.
Methods We compared temperature trends between urban and reference stations and conducted linear regressions to evaluate the city- and local-scale influences, based on meteorological data and remote sensing data.
Results Urbanization significantly influenced trends of the air temperature, especially in summer. Trends of the mean temperature caused by urbanization was 0.3–0.4 °C decade^{-1} yearly and 0.4–0.6 °C decade^{-1} in summer. The increase of city size and the proportion of local developed land both contributed to urban warming, but their relative importance changed over time and varied seasonally. The local-scale factor played a vital role for the air temperature when the city size was relatively small, and were more important in summer when there was more greenspace at the local scale. However, the city-scale factor may cause stronger heat stress in summer, if there was less greenspace locally. When the city size was very large, the city-scale factor became the only significant factor affecting the air temperature.
Conclusions When a city is relatively small, optimizing the composition or configuration of the local land cover could effectively alleviate UHI effects. However, when the city is already large, a more effective way is to control additional sprawl.

Keywords Urban heat island · Air temperature · Urbanization · City size · Local land cover · Beijing · Landsat · Scale · Mitigation

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Introduction

Urban heat island (UHI) refers to the phenomenon that air or land surface temperatures in urban areas are higher than surrounding exurban or rural regions. It is a common thermal problem faced by cities, which can not only increase urban energy use, exacerbate air pollution, change the hydrologic cycle and biodiversity, but also directly influence human health and comfort (Baker et al. 2002; Sailor and Fan 2002; Poumadere et al. 2005; Gaffin et al. 2008; Chen et al. 2010; Huang et al. 2011; Feizizadeh and Blaschke 2013; Huang and Cadenasso 2016). The generation of UHI is largely due to the inherent structure and function of cities. Cities generally have more buildings and paved surfaces that boost thermal mass. Less greenspace and fewer surface water bodies reduce the ability of a city to cool down through evapotranspiration (Oke 1982; Buyantuyev and Wu 2010; Santamouris 2013a; Ma et al. 2016; Peng et al. 2016). Cities also have more complex vertical structure (e.g., high-rise and low-rise buildings) than their surroundings, which may influence absorption and exchange of heat (Oke 2002, 2004). In addition, intensive human activities may generate anthropogenic heat, such as the released heat from factories, air conditioners and vehicles, leading to severe thermal loads (Taha 1997; Ichinose et al. 1999; Stone et al. 2010; Myint et al. 2013).

Rapid urbanization can exacerbate the UHI effect or warm the urban areas through urban expansion and local land-cover change (Pielke and Avissar 1990; Oke 1995; Voogt and Oke 2003; Yuan and Bauer 2007; Connors et al. 2013). Two types of land changes are generally associated with urbanization processes: (1) urban expansion occurring mostly on the city fringes, and (2) transformations of the land cover within cities due to the infill, redevelopment or greening (Forman 2014; Qian et al. 2015). The temperature at a certain location in a city is influenced by both local-scale factors, such as the surrounding land cover/land use, and by city-scale factors such as the expanded city size. These factors at these two scales operate through different mechanisms (Oke 1976; Nichol et al. 2009). Under global warming, urban areas are expected to have a higher risk of suffering from extreme heat events, due to their already existing UHI (Basara et al. 2010; Tan et al. 2010; Wang et al. 2013; Ma et al. 2014). Since more than 52% of the world population are now urban dwellers, urban planners and policy makers are eager to enhance their understanding on the relationship between urbanization and UHI, in order to mitigate heat stress, improve the quality of life, and achieve urban sustainability (Chow et al. 2012; Wu et al. 2014; Zhou et al. 2016).

The relationship between UHI, especially as indicated by air temperature, and city-scale factors has long been the focus of UHI studies (Oke 1973; Karl et al. 1988; Stone et al. 2010; Yang et al. 2011). For example, Oke's (1973) classic article quantified the relationship between urban population size and UHI, suggesting that larger cities would have higher air temperatures than smaller cities. Many other studies also showed positive correlations between city size and the intensity of UHI or absolute temperatures (Karl et al. 1988; Brazel et al. 2000; Goggins and Choi 2008; Fujibe 2009; Imhoff et al. 2010). The growth of cities significantly increases the temperature of urban areas (Zhou et al. 2004; Georgescu et al. 2012; Wang et al. 2013). Moreover, urban areas with sprawling extents are considered to receive more extreme heat events (EHEs; Gaffen and Ross 1998; Stone et al. 2010). The fact that the growth of the city size leads to intensified UHI may be explained by the advection model and the urban sprawling effects (Oke 1976; Nichol et al. 2009; Stone et al. 2010). With the expansion of the city, cooler air that moves inward from the surrounding non-urban areas would influence a smaller proportion of the city (Oke 1976; Nichol et al. 2009). Moreover, larger cities are more likely to have taller buildings and more complex landscape patterns, which would concentrate more heat (Oke et al. 1999; Grimmond 2007). In addition, larger cities tend to generate more anthropogenic heat due to more human activities, for example, more vehicles, longer commuting distance, and more air conditioners (Stone et al. 2010).

In addition to city-scale factors, local-scale factors, such as types of land use/land cover (LULC), their proportional covers and spatial configurations, can significantly affect the thermal environment (Owen et al. 1998; Voogt and Oke 2003; Unger 2004; Weng et al. 2004; Buyantuyev and Wu 2010; Emmanuel and Krueger 2012; Radhi et al. 2013). Previous studies have shown that the built-up land, industrial zones, commercial regions and roads were hotter, while the vegetated land, such as parks, along with lakes and rivers are cooler (Weng and Yang 2004; Chen et al. 2006, 2012b; Hart and Sailor 2009; Li et al. 2011; Radhi et al. 2013). In particular, the proportion of greenspace, canopy cover, or NDVI was strongly and negatively correlated with land surface temperature (LST), while the proportion of developed land or impervious surfaces had strong positive correlations with the LST (Hart and Sailor 2009; Zhou et al. 2011; Connors et al. 2013; Lazzarini et al. 2013; Petralli et al. 2014; Ma et al. 2016). Landscape metrics representing the configuration of different LULC types, such as patch density (PD), landscape shape index (LSI), sky view factor (SVF) and other 2D and 3D metrics, had less or equal, positive or negative relationships with UHI due to the differences in study areas or methods (Unger et al. 2004; Zhou et al. 2011; Chen et al. 2012a; Li et al. 2012, 2013). For example, Zhou et al. (2011) found that PD of greenspace was positively correlated to LST, and LPI of greenspace was negatively correlated to LST. Integrated indices such as the local climate zone (LCZ) have been developed to examine the effects of the local LULC on temperatures (Stewart and Oke 2009, 2012; Emmanuel and Krueger 2012). However, in general, the proportions of developed land or impervious surface and greenspace are the most important factors in the thermal environment at the local scale (Owen et al. 1998; Huang et al. 2010; Imhoff et al. 2010; Zhou et al. 2011, 2014).

Few studies, however, have investigated the joint effects of these two different scale factors, or quantified their relative contribution to urban warming. Here, we investigated the joint effects of urban expansion and local land-cover change on urban warming, and further quantified their relative importance over time. We focused on Beijing, the capital of China, which has been undergoing rapid urban expansion since the 1980s. We used air temperature data collected at 20 national weather stations from 1983 to 2010, and land classification data derived from Landsat TM/ETM+ images in 1984, 1990, 2000 and 2010 to measure city size and local land cover. Results from this study can enhance our understanding on how urban expansion and within-city local land-cover change together affect urban warming, and provide insights for urban planning and management.

Study area

Beijing municipality (Fig. 1a) is located in the northwest of the North China Plain, and is approximately 16,411 km^2 in size. It is in the warm temperate zone with a continental monsoon climate. The monthly mean temperature ranges from −3.1 to 26.7 °C, with the average precipitation of 532 mm per year. The western and the northern parts of Beijing municipality are mountainous, with elevations ranging from 100 m to more than 2000 m. The remainder is in the plain, where the extensive urbanization is occurring. Beijing is the capital of China, serving as the national political, cultural, technological and international center. It has a total population of more than 22 million. The area of developed land increased from 366 km^2 in 1984 to 1426 km^2 in 2011, and GDP increased from approximately 10 billion yuan in 1978 to more than 1950 billion yuan in 2013 (National Bureau of Statistics of the People's Republic of China).

Data and methods

Data and preprocessing

Land cover data and city boundaries

Land cover data were derived from Landsat TM/ETM+ images collected on October 3, 1984, September 18, 1990, October 31, 2000 and June 5, 2010, when vegetation was mostly leaf-on. We also used images in July or August that were one year before or after to refine the classification results. For example, we used data from August 31, 2001 and July 20, 2009 to refine the classification results in 2000 and 2010, respectively. We used an approach that integrates objected-based classification and backdating, with extensive manual editing for refinement (Yu et al. 2016). The method first detects objects with changes using spectral information, shapes and relationships to their neighboring objects, and then conducts classifications on those objects with changes (Yu et al. 2016). Consequently, the overall accuracy of the classification maps in 1984 and 1990 was approximately 85%, and more than 90% in 2000 and 2010. Six land cover classes were included in the classification: forest land, grassland, cultivated land, water, developed land and barren. We combined two classes, forest land and grassland into greenspace in analysis.

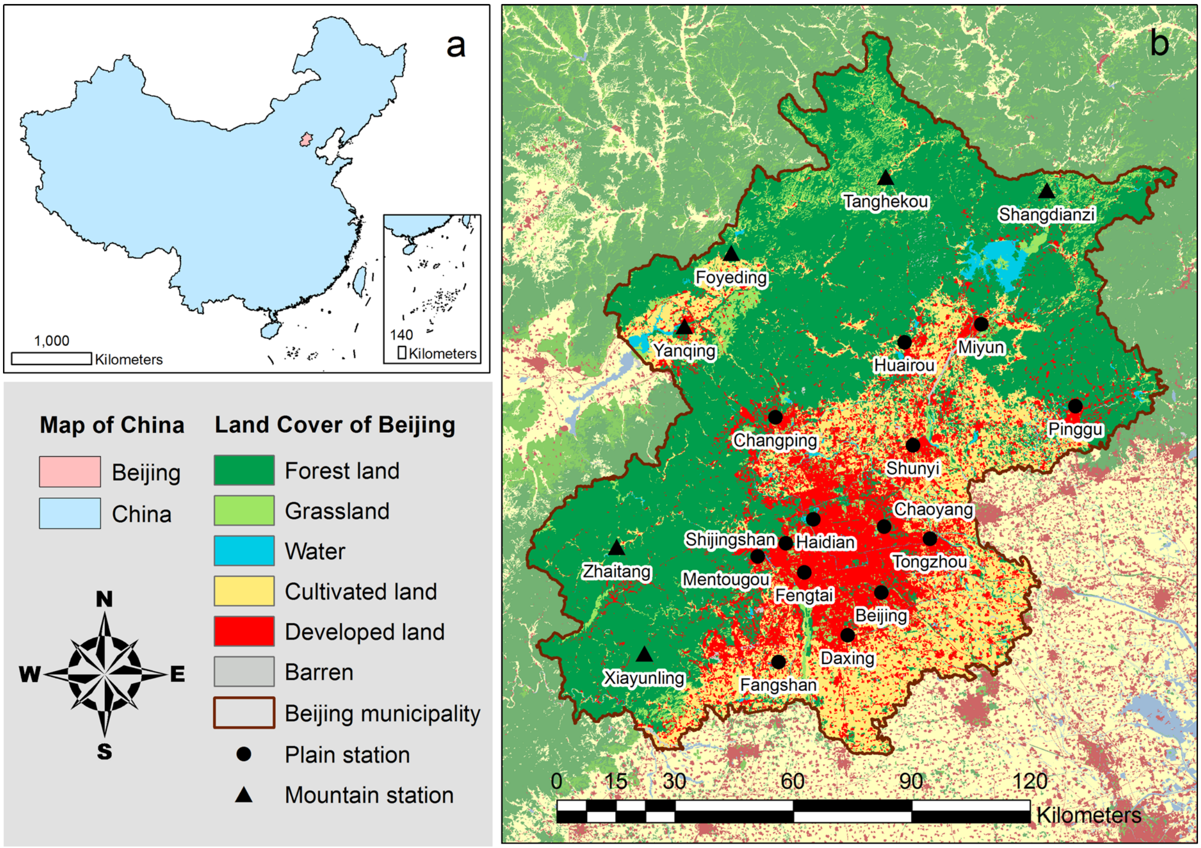

Fig. 1 **a** The location of Beijing municipality. **b** The spatial distribution of weather stations in Beijing, overlaid on the 2010 land cover data

We used the boundary of the core area of Beijing municipality to represent the boundary of Beijing city in terms of developed land, for the majority of the land within this large municipality is undeveloped. That is, developed land comprised approximately 0.05–10% of the municipality area from 1984 to 2010. Despite the existence of an intensively urbanized core area, there are a variety of different sized satellite cities, towns and villages dispersed throughout Beijing municipality. The core area was the largest continuously developed region of Beijing municipality, where most human activities occurred. We excluded satellite cities, towns and villages within the larger municipality of Beijing, and the core urban region of developed land was called Beijing city.

Based on the 30 m resolution land-cover classification data, we created grids with a size of $900 \times 900\ m^2$ to delineate the boundary of the core area, using ArcGIS™ version 10.2. Previous studies showed that 800–1000 m was the most appropriate size to extract the boundary of such a big city (Hu et al. 2015). Here we chose the size of 900 m because it is 30 times of the spatial resolution of TM/ETM+ data (i.e., 30 m). Specifically, we first identified all the grids with more than 50% developed land. These grids were then dissolved to one big polygon, which represented the major part of the core area, and many scattered smaller ones. We further refined the extent of the core area by: (1) removing the scattered polygons that did not connect with the big polygon, and (2) dissolving the grids with less than 50% of developed land but totally encompassed by the big polygon. Therefore, the core area was extracted as Beijing city, which provided the boundary of the urban category in our analysis. We delineated boundaries of Beijing city in 1984, 1990, 2000 and 2010 separately (Fig. 2).

Weather stations and the air temperature data

The daily mean, maximum and minimum temperatures during 1983–2011 were derived from 20 national

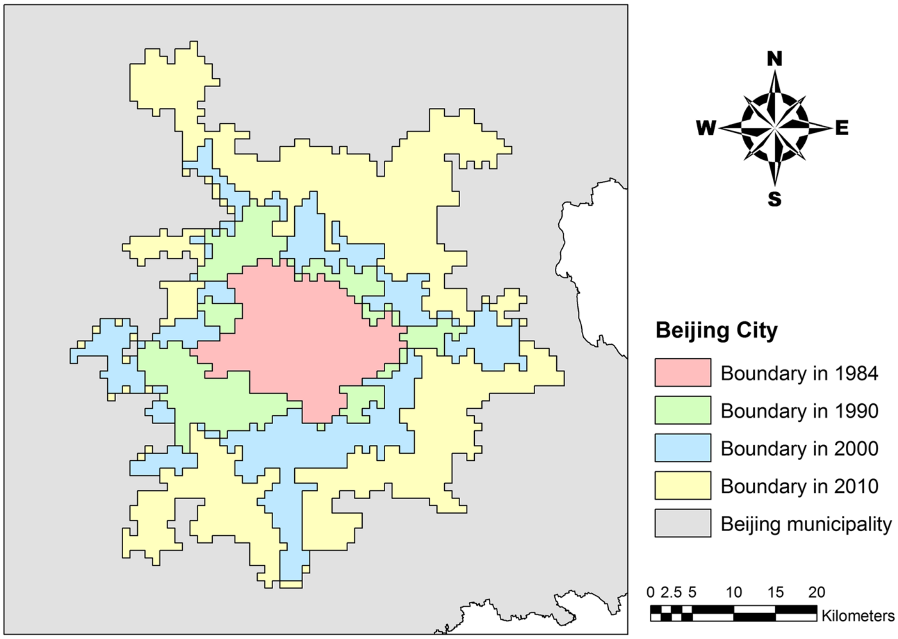

Fig. 2 Boundaries of Beijing City in 1984, 1990, 2000 and 2010

weather stations in Beijing (Fig. 1b). These stations were established following the World Meteorological Organization (WMO) standards, and thus have similar site environments and maintenance (Liu et al. 2007). Each temperature record includes the longitude/latitude (degree, minute) and the elevation (0.1 m) of the station, along with a quality verification code. With the longitude and latitude of each station, by referring to historical images from Google Earth, we identified the accurate location for each of the stations in different time period.

Because some of the weather stations in Beijing have been relocated since they were established (Si et al. 2009; Yan et al. 2010), it is necessary to conduct a homogeneity check before using the air temperature data for long-term analysis (Li et al. 2004). We first identified the years when the longitude/latitude or the elevation of the stations changed. We only used data from stations that never relocated to analyze the long-term temperature variation from 1983 to 2011. When quantifying the local land-cover proportions of a given station, we used the location of that station at the specific year. It is therefore reliable to conduct temperature comparisons among these stations.

We classified the 20 weather stations into three types to investigate temperature variations and evaluate the urbanization impact. Considering the varied topography and rapid urbanization in Beijing, we first separated six stations located in the mountain areas from the 14 stations located in the plain (Table 1; Fig. 1b). Direct temperature comparisons between these two types of stations largely showed altitude differences, but the trends of the temperature could be compared (Ren et al. 2007). Four out of the six mountain stations, excluding Yanqing and Zhaitang stations, were located in natural or rural areas that received little impact from urbanization, and thus could be used reliably as reference stations. The 14 plains stations were located in the rapidly developing areas of Beijing municipality, and received a greater impact from urbanization. These stations were considered as urban stations. We further divided these 14 urban stations into two types, based on the boundaries of Beijing city in 1984, 1990, 2000 and 2010, respectively (Figs. 2, 3). Stations within the city boundary were referred to as city stations, and the others as outer-city stations. We used urban and reference stations to evaluate the overall impact of urbanization in Beijing municipality. We used city and outer-city stations to quantify the city- and local-scale factors of urbanization in the urban area of Beijing.

Table 1 Weather stations in Beijing

Station	Shunyi	Beijing	Pinggu	Chaoyang	Daxing
Elevation(m)	28.6	31.3	32.1	35.3	37.6
Final move	1999.1	1997.4	2006.1	2007.1	2003.1
Location	Plain	Plain	Plain	Plain	Plain
Station	Fangshan	Tongzhou	Haidian	Fengtai	Shijingshan
Elevation(m)	39.2	43.3	45.8	55.2	65.6
Final move	2006.1	1995.1	2004.1	1978.1	1998.1
Location	Plain	Plain	Plain	Plain	Plain
Station	Huairou	Miyun	Changping	Mentougou	Shangdianzi
Elevation(m)	75.7	71.8	76.2	92.7	293.3
Final move	1996.7	1982.9	2003.4	1978.1	1988.1
Location	Plain	Plain	Plain	Plain	Mountain
Station	Tanghekou	Xiayunling	Zhaitang	Yanqing	Foyeding
Elevation(m)	331.6	407.7	440.3	487.9	1224.7
Final move	1982.9	1982.9	1974.8	1982.9	1978.1
Location	Mountain	Mountain	Mountain	Mountain	Mountain

Methods

Comparisons of temperature trends between urban and reference stations

We compared the temperature trends between urban and reference stations during 1983–2011 to examine the overall impact of urbanization on urban warming. We used Xiayunling, an unmoved mountain station with a relatively low altitude, as the reference. This station is located in a national forest park. Two unmoved plain stations, Fengtai (Being inside Beijing city since 1984–1990) and Mentougou (Being inside Beijing city since 1990–2000), were selected as urban stations. These two urban stations could stand for the earlier developed and the later developed urban areas, respectively.

We calculated the annual mean, maximum and minimum temperatures, as well as the mean, maximum and minimum temperatures in summer (June, July, and August) and winter (December, next-year January and February) for each year from the weather stations. The temperature trends during 1983–2011 were fitted by the ordinary least square (OLS) model, annually and seasonally. We anticipated differences in the trends between each of the two urban stations and the reference station. Thus, we used both of the trend differences (Fengtai–Xiayunling and Mentougou–Xiayunling) as an approximate range, instead of an average number, to show the extent of the impact of urbanization. For example, the difference in the annual mean temperature trend between Fengtai and Xiayunling was 0.42 °C decade^{-1}, and the difference between the Mentougou and Xiayunling trends was 0.28 °C decade^{-1}. Therefore, the overall extent of warming on the annual mean temperature of Beijing urban area caused by urbanization during 1983–2011 was about 0.28–0.42 °C decade^{-1}.

City expansion and changes of land cover surrounding the urban stations

The city size in 1984, 1990, 2000 and 2010 was calculated based on the boundaries of Beijing city delineation, as described in 3.1.1. The annual increase in city size was then calculated for three periods: 1984–1990, 1990–2000 and 2000–2010.

Buffers with a radius of 1 km were generated for each of the 14 urban stations, within which the proportions of developed land, greenspace, cultivated

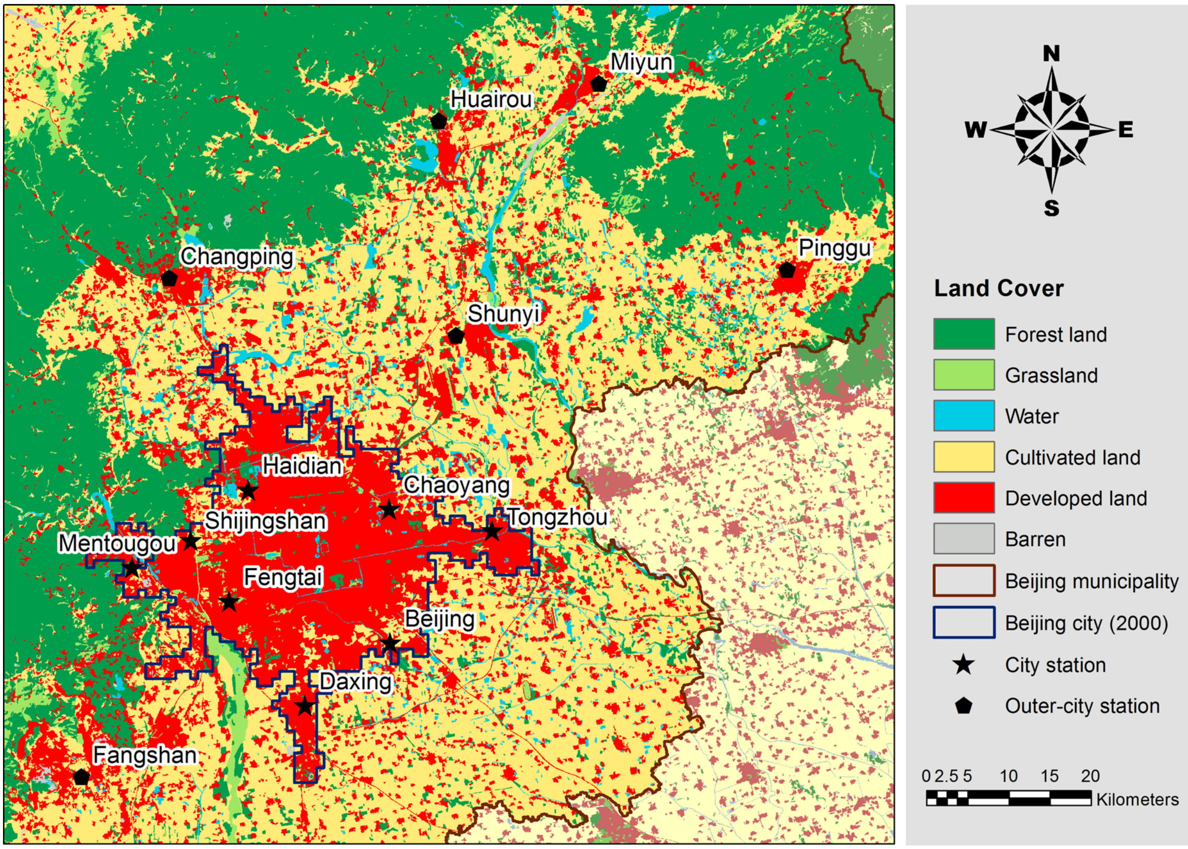

Fig. 3 City and outer-city stations in relation to the boundary of Beijing city in 2000, overlaid on 2000 land cover data

land, water and barren were calculated. We used the 1-km buffer because this scale has been shown to play a major role to the local climate (Brazel et al. 2007; Forman 2014). We used box plots to compare the proportional distributions of developed land, green-space and cultivated land between city and outer-city stations.

Impact of the city- and local-scale urbanization on the air temperature

We used the city size as the city-scale factor that influenced the air temperature of city stations, and the impact was evaluated by the differences in temperature between city and the outer-city stations. We assumed that if the weather station was inside the city, then the city would be a larger-scale factor that influenced the temperature of the station by mechanisms mentioned in the Introduction. The magnitude of the impact depends on city size. The average temperature differences between city and outer-city stations were calculated for 1984, 1990, 2000 and 2010, based on annual, summer and winter mean temperatures. Kolmogorov–Smirnov (K–S) tests were conducted to evaluate whether temperatures of city and outer-city stations were significantly different ($\alpha = 0.05$). The K–S test is a nonparametric and distribution-free test used to determine whether the two datasets are significantly different from each other (Lilliefors 1967).

The proportion of developed land within the 1-km buffer of the 14 urban stations was used as the indicator of the local-scale factor that influenced air temperature. We used scatter plots and the OLS regression model to examine the relationships between the proportions of developed land and air temperature, qualitatively and quantitatively. We used the proportional cover of developed land as the local-scale factor, because: (1) developed land is the major land cover type in urban areas that influences local temperature the most, and (2) developed land changed relatively little compared to greenspace or cultivated land through the year. Therefore, stable relationships could be analyzed.

We used multiple linear regressions to examine the relative importance of the city- and local-scale factors to the annual and seasonal temperatures in 1984, 1990, 2000 and 2010. In the regressions, the annual, summer and winter temperatures of the 14 urban stations in each of the four years were used as dependent variables. Independent variables, i.e., predictors, contained both the local-scale factor, that is, the proportional cover of developed land within the 1-km buffer of each station, and the city-scale factor, that is, whether the station was within the city or not. We created a dummy variable to represent the city-scale factor, with "1" meaning the station was inside the city, and '0' meaning not.

Results

Intensified UHI from 1983 to 2011

We found UHI intensified from 1983 to 2011, as indicated by the differences in the mean, minimum and maximum temperature trends between urban and reference stations (Fig. 4; Table 2). Differences in the mean and minimum temperatures, however, were greater than differences in the maximum temperatures, suggesting the urban growth in Beijing had greater impacts on the mean and minimum temperatures. Trends in the mean and minimum temperatures were similar, with larger warming trends in the urban stations compared to the reference station (Table 2). Trend differences between the maximum temperatures in the urban and reference stations were smaller (Table 2).

Warming trends caused by urbanization were generally larger in summer in terms of the mean and maximum temperatures, while the minimum temperature had similar trend differences annually and seasonally (Table 2). The urban stations had the largest warming trends in summer and the lowest in winter. The reference station showed stable or small increasing trends in the annual and summer temperature, and stable or declining trends in the winter temperature (Fig. 4; Table 2). For example, the warming trend in mean temperature for Fengtai was 0.55 °C $decade^{-1}$ in summer, 0.28 °C $decade^{-1}$ in winter and 0.47 °C $decade^{-1}$ year around. Meanwhile, the reference station, Xiayunling, showed nearly no changing trend for the summer and annual mean temperatures, and a negative trend of −0.12 °C $decade^{-1}$ for the mean in winter. Although there were decreasing trends in the winter temperature for the reference station, the urban stations had much smaller trends for warming in winter. Therefore, the differences in the trends for the mean and maximum temperatures were larger in summer and smaller for winter and year-around (Table 2).

City expansion and temperature differences between city and outer-city stations

Beijing city has expanded rapidly since 2000. The area of the city enlarged by approximately six times from 277.83 km^2 in 1984 to 1913.22 km^2 in 2010. The rates of the increase were similar during the period of 1984–1990 and 1990–2000, being 43.74 and 44.87 $km^2\ a^{-1}$, respectively. However, during 2000–2010, the rate doubled to 92.42 $km^2\ a^{-1}$, which indicates an acceleration (Fig. 5).

Along with city expansion, more weather stations located in Beijing city, and the differences in the annual, summer and winter mean temperatures between city and outer-city stations increased as well. There were only two city stations in 1984, and the number of city stations increased to four, eight and 10 in 1990, 2000 and 2010, respectively. The differences in temperature were similar in 1984 and 1990, then sharply increased in 2000, and doubled in 2010 compared to those in 1984 (Fig. 5). K–S tests showed that the annual mean temperatures between city and outer-city stations were significantly different since 2000, while the summer and winter mean temperatures were significantly different since 1990 (Table 3).

Local land-cover change and its correlations with air temperatures

From 1984 to 2010, the proportions of developed land within the 1-km buffers increased, and the proportion of cultivated land declined. Meanwhile, the proportions of greenspace increased rapidly since 2000 (Fig. 6a). The proportion of cultivated land was 55% in 1984, but consistently declined since then. In contrast, the proportion of developed land continuously increased, becoming the dominant land cover type in 1990, and reaching nearly 70% in 2000

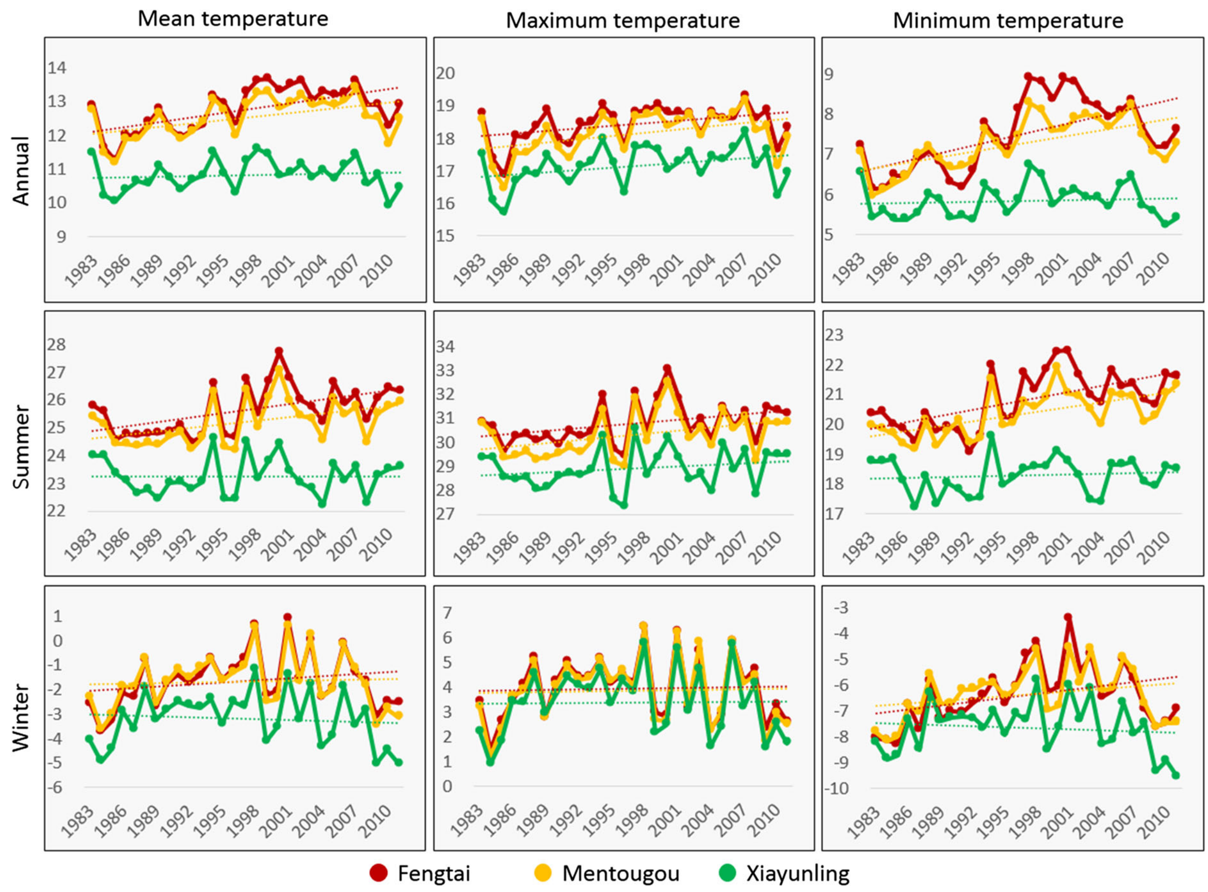

Fig. 4 Trends of annual and seasonal mean, maximum and minimum temperatures of two urban stations (Fengtai and Mentougou) and the reference (Xiayunling) from 1983 to 2011

(Fig. 6a). The proportion of greenspace cover also greatly increased since 2000, from approximately 4% during 1984–1990 to 7% in 2000, and finally up to 19% in 2010. The increases in other types, such as wetland, were very small (<2%), and changed little over the decades measured (Fig. 6a).

The overall trends of the local land-cover change were similar between city stations and outer-city ones. The medians and deviations of the proportional cover of land-cover types differed greatly between city and outer-city stations for each of the time slices (Fig. 6b–d). In general, city sites had higher medians and lower deviations in developed land, and outer-city sites had higher medians and higher deviations in cultivated land (Fig. 6b, d). The proportion of greenspace increased in both the city and outer-city stations since 1984. City sites had higher medians of greenspace in 1984 and 2010, and outer-city sites had higher deviations than city sites except in 2000 (Fig. 6c).

The proportion of developed land at the local scale had significant and positive linear correlations with the annual, summer and winter mean temperature since 1990 (Fig. 7; Table 4). The β coefficients of the regression models increased from 1990 to 2010 (Table 4), with many of the observations clustered around values of high developed land proportions and high air temperatures (Fig. 7). The correlations between the proportions of developed land and air temperatures were most significant in 2000, where all the *P* values were below 0.01.

Relative importance of the city- and local-scale factors for the temperature variation from 1984 to 2010

The city of Beijing expanded at an accelerated rate from 1984 to 2010, and the local land cover changed as well. Consequently, the relative importance of urban

Table 2 Differences of warming trends between urban stations and the reference station

Time	Trend differences	Stations	Mean temperature		Station	Maximum temperature		Station	Minimum temperature	
			Warming trend (°C decade^{-1})	Difference (°C decade^{-1})		Warming trend (°C decade^{-1})	Difference (°C decade^{-1})		Warming trend (°C decade^{-1})	Difference (°C decade^{-1})
Annual	Maximum difference	Fengtai	0.47	0.42	Mentougou	0.34	0.11	Fengtai	0.65	0.61
		Xiayunling	0.05		Xiayunling	0.23		Xiayunling	0.05	
	Minimum difference	Mentougou	0.33	0.28	Fengtai	0.26	0.03	Mentougou	0.47	0.42
		Xiayunling	0.05		Xiayunling	0.23		Xiayunling	0.05	
Summer	Maximum difference	Fengtai	0.55	0.55	Mentougou	0.43	0.23	Fengtai	0.68	0.60
		Xiayunling	−0.00		Xiayunling	0.20		Xiayunling	0.08	
	Minimum difference	Mentougou	0.43	0.43	Fengtai	0.38	0.18	Mentougou	0.54	0.46
		Xiayunling	−0.00		Xiayunling	0.20		Xiayunling	0.08	
Winter	Maximum difference	Fengtai	0.28	0.40	Mentougou	0.07	0.05	Fengtai	0.51	0.65
		Xiayunling	−0.12		Xiayunling	0.02		Xiayunling	−0.14	
	Minimum difference	Mentougou	0.09	0.21	Fengtai	0.06	0.04	Mentougou	0.32	0.46
		Xiayunling	−0.12		Xiayunling	0.02		Xiayunling	−0.14	

expansion and LULC changes for the air temperature altered.

For the annual mean temperature, the local-scale factor showed its significant impact on the air temperature earlier, while the city-scale factor became more and more important later in the study period. For example, in 1984 the effects of both developed land cover at the local scale and whether or not a meteorological station was within the city were not significantly related to the temperature variation (Table 5). In 1990, the local-scale factor became significantly related to annual mean temperature, but the city-scale factor remained insignificant. In 2000, both the local and the city-scale factors had significant contributions to the variation of air temperature, but the city-scale factor was more important. By 2010, only the city-scale factor influenced the air temperature significantly (Table 5).

As for seasonal differences, the local-scale factor showed a larger impact in summer than in winter, while the city-scale factor explained more variation in mean winter temperature (Table 5). In 2000, both the local- and city-scale factors significantly influenced air temperatures, but the local-scale factor explained more of the variation in summer (61.5%), while the city-scale factor explained more variation in winter (64.2%). Although the local-scale factor was not a significant contributor to the air temperature in 2010 when compared to the city-scale factor ($\alpha = 0.05$), it explained 32.7% of the temperature variation in summer with marginal significance ($\alpha = 0.1$; Table 5).

Discussion

Obvious urban warming occurred in Beijing

We found a clear warming trend in temperature along with the rapid urbanization in Beijing from 1984 to 2010. This result is similar to the findings from previous studies conducted in Beijing, as well as in other cities (Liu et al. 2007; Ren et al. 2007; Yan et al. 2010; Fujibe 2011). Here, based on unmoved urban and reference stations, we showed an excess warming trend of 0.3–0.4 °C decade^{-1} in the annual mean temperature in Beijing due to urbanization. This magnitude in warming is close to, or slightly greater than previous studies conducted in Beijing, that used

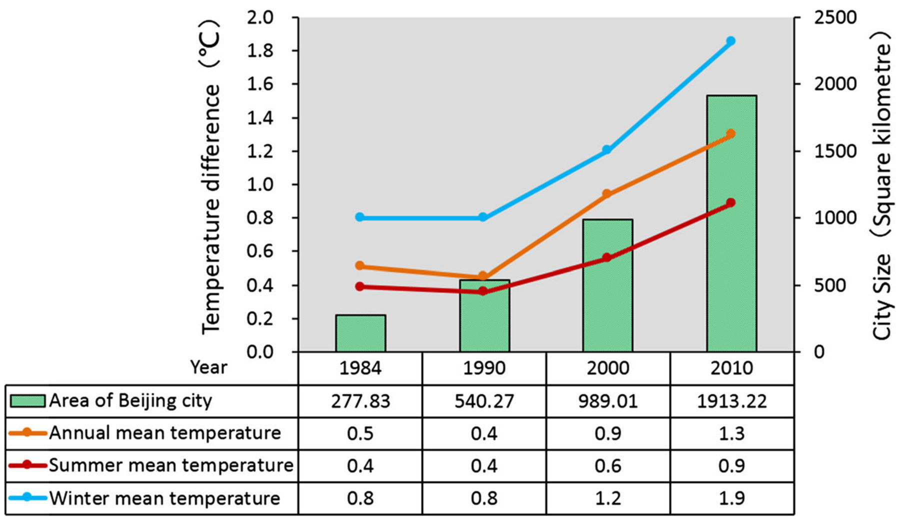

Fig. 5 Expansion of Beijing city and differences of the annual and seasonal mean temperatures between city stations and outer-city stations from 1984 to 2010

Table 3 Results of Kolmogorov–Smirnov tests on differences of temperatures between city and outer-city stations

Year	Annual mean temperature	Summer mean temperature	Winter mean temperature
1984	0.185	0.604	0.065
1990	0.052	0.007**	0.020*
2000	0.010*	0.042*	0.010*
2010	0.007**	0.007**	0.007**

* Coefficient is significant at the 0.05 level (two-tailed)

** Coefficient is significant at the 0.01 level (two-tailed)

different methods for station selection (Liu et al. 2007; Ren et al. 2007; Yan et al. 2010). In addition, we found the mean and minimum temperatures were more strongly influenced by urbanization than the maximum temperature, a result similar to previous studies (Kalnay and Cai 2003; Zhang et al. 2005; Liu et al. 2007; Trusilova et al. 2008; Zhou and Ren 2009; Fujibe 2011; Wang et al. 2013). This may be because the maximum temperature is determined mostly by the solar radiation, but the minimum temperature is influenced greatly by the heat storage in buildings and pavements that is gradually released during the night (Oke 1982).

The excess increase of 0.3–0.4 °C decade^{-1} caused by urbanization in Beijing is generally greater than that reported from other large or rapidly developing cities around the world. For example, Shanghai, China, a city with the similar size of Beijing that also experiencing a rapid growth, had an excess increase of 0.23 °C decade^{-1} in annual mean temperature from 1951 to 2006 (Cao et al. 2008). Dehradun, a megacity with rapid expansion in northern India, had an excess increase of 0.28 °C decade^{-1} from 1988 to 2007 because of urbanization, four times higher than 0.06 °C decade^{-1} from 1967 to 1987 (Singh et al. 2013). Large cities in Japan, such as Tokyo and Osaka, had an excess warming trend of 0.18 and 0.14 °C decade^{-1} during 1931–2008 (Fujibe 2011). Vienna, a well-developed city with nearly constant population from 1951 to 1995, showed an excess temperature trend of 0.13 °C decade^{-1} due to changes in urban morphology and energy use (Böhm 1998). Developing cities seemed to have larger warming trends because of rapid sprawling and population growth. The warming trend in Beijing was large even among developing cities.

The positive trend of increasing temperatures was more prominent in summer than in winter, or annual average, which should concern urban managers and citizens as well. There was an excess increase of

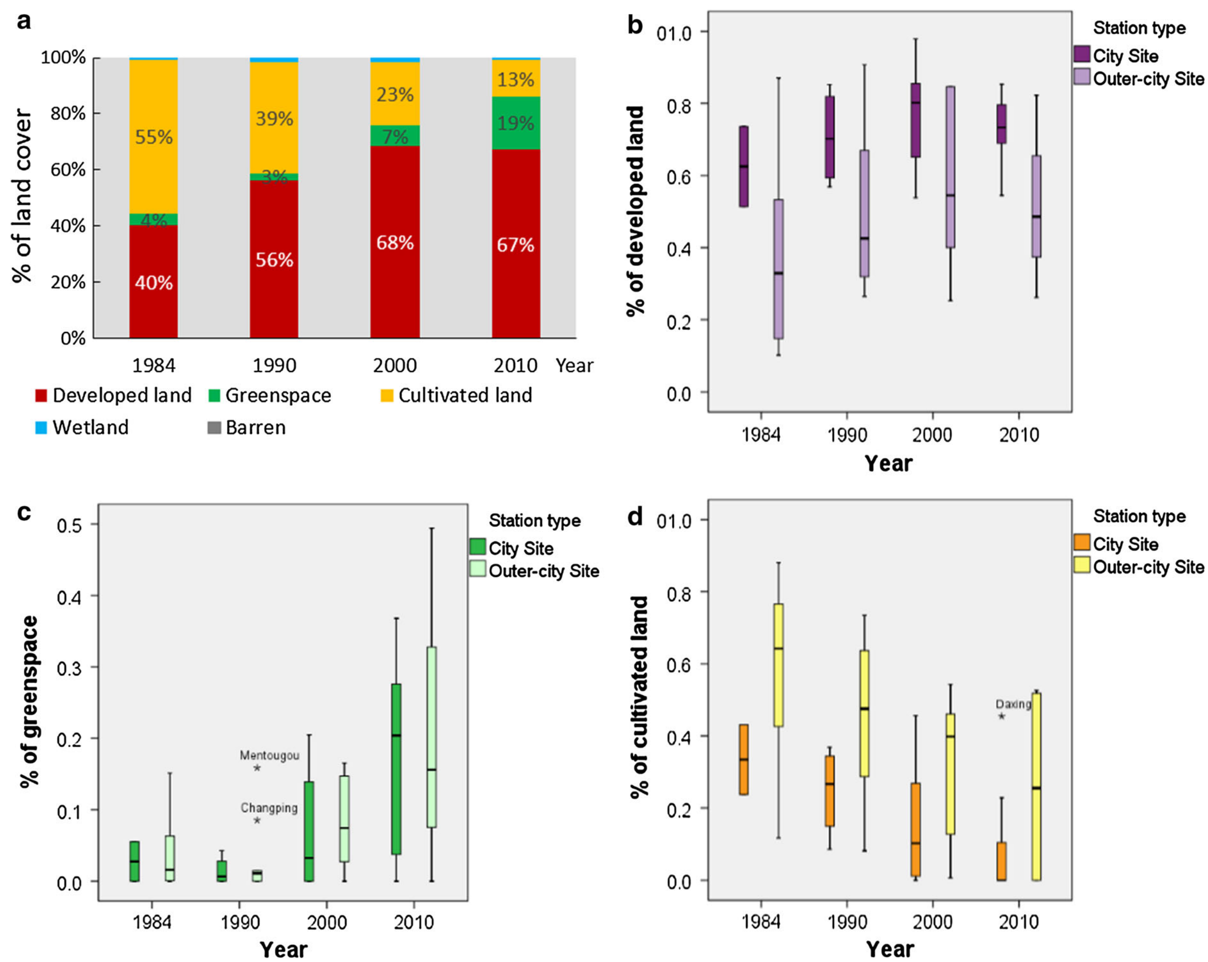

Fig. 6 Compositions of local land cover from 1984 to 2010

0.4–0.6 °C decade^{-1} of the mean temperature in summer, much bigger than that of 0.2–0.4 °C decade^{-1} in winter and 0.3–0.4 °C decade^{-1} annually. The warming in summer increases energy use for cooling, which would in turn result in more waste heat and thus higher air temperature (Ohashi et al. 2007). Hotter summers may cause more heat-related illness and deaths because of extreme heat events (Tan et al. 2010; Wong et al. 2013). For example, the 1995 heat wave in Chicago and the 2003 heat wave in Europe caused 514 and about 35,000 excess deaths, respectively (Whitman et al. 1997; Hartz et al. 2012). Beijing serves as the national political, cultural, technological and international center of China. In addition to the large population (more than 22 million) of permanent residents, several million people visit Beijing each year for different purpose. Many of them visit Beijing in summer when the temperature is very high. Therefore, it is necessary for Beijing to pay more attention to the heat stress in summer.

The relative importance of the city- and local-scale factors varied over time

The accelerating expansion of Beijing city made the city-scale factor of increasing importance to the variation of the annual mean temperature, highlighting the need to control the size of the city for managing UHI. In 1984, the city size was small and had no significant impact on the air temperature (Table 5). Meanwhile, at the local scale, developed land was not dominant, and showed no significant impact on temperature either (Table 5). This is likely due to the fact that low-rise buildings within the city had similar

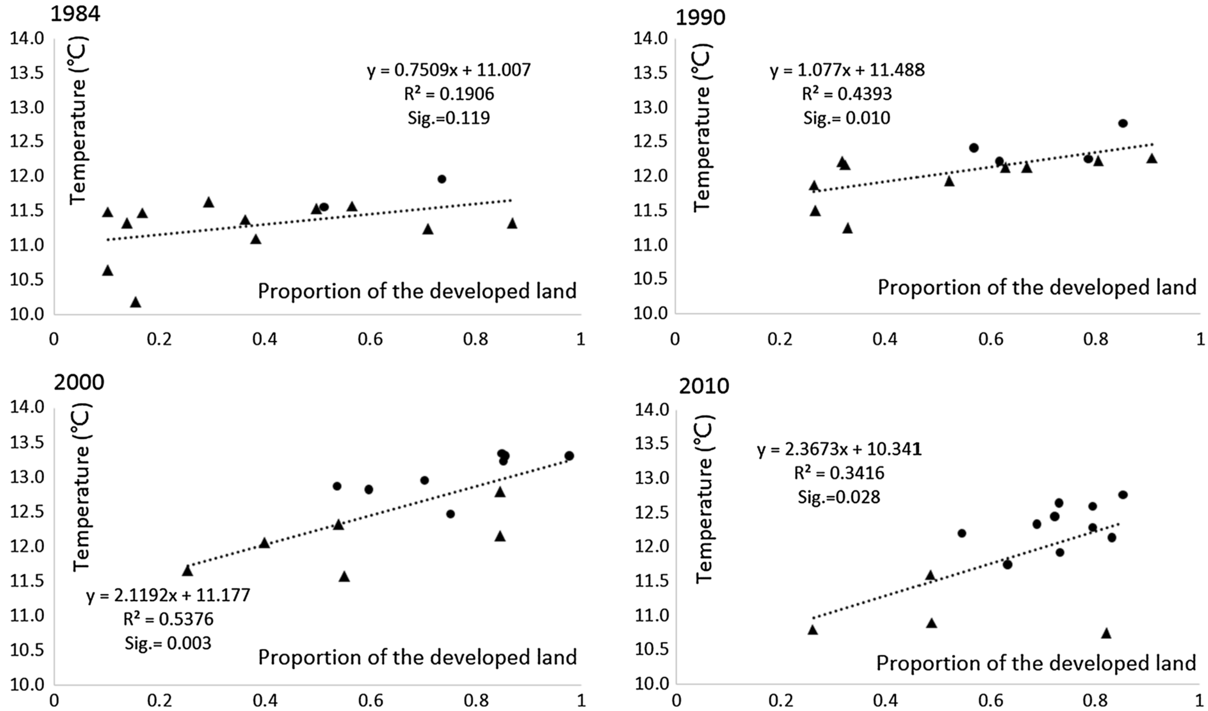

Fig. 7 Relationships between the proportions of the developed land and the mean temperature

Table 4 Linear regression results of the mean temperature and the proportion of the local developed land

Year	Annual mean temperature			Summer mean temperature			Winter mean temperature		
	B	Constant	Sig.	B	Constant	Sig.	B	Constant	Sig.
1984	0.751	11.007	0.119	0.416	24.988	0.285	0.875	−4.442	0.240
1990	1.077	11.488	0.010**	0.653	24.403	0.021*	1.967	−3.144	0.017*
2000	2.119	11.177	0.003**	1.605	26.036	0.001**	2.513	−4.481	0.008**
2010	2.367	10.341	0.028*	2.054	24.748	0.003**	3.228	−4.870	0.034*

* Coefficient is significant at the 0.05 level (two-tailed)

** Coefficient is significant at the 0.01 level (two-tailed)

thermal attributes with cultivated lands outside the city (Stewart and Oke 2012; Forman 2014). In the late 1980s, Beijing implemented a decentralized development policy, and as a result, both Beijing city and the remote satellite cities or towns began to develop rapidly. Although Beijing city and the other cities or towns were different in size, they all had similar patterns and heights of buildings. This explained why the local-scale factor was significantly correlated to the temperature in 1990, and was the most important factor contributing to the variation of the annual mean temperature (51.9%, $P = 0.042$; Tables 4, 5). With the continuous growth of Beijing city, both the city- and the local-scale factors became significant in 2000. However, the city-scale factor explained more variation in the annual mean temperature (Table 5). In 2010, the city size doubled to 1913.22 km^2. Consequently, the city-scale factor became the overwhelming factor for the air temperature, despite the fact that the proportion of developed land decreased and the greenspace increased by 12% at the local scale. In other words, when the size of the city becomes very large, local regulations that promote the addition of greenspace will be less efficient for heat mitigation.

In summer, the local greening efforts can be more effective than in other seasons if there are more

Table 5 Linear regression results of the relative contributions of the local- and city-scale factors

Year	Annual mean temperature				Summer mean temperature				Winter mean temperature			
	R^2	Adjusted R^2	Beta: inside the MBA or not (Sig.)	Beta: % of the developed land (Sig.)	R^2	Adjusted R^2	Beta: inside the MBA or not (Sig.)	Beta: % of the developed land (Sig.)	R^2	Adjusted R^2	Beta: inside the MBA or not (Sig.)	Beta: % of the developed land (Sig.)
1984	0.268	0.135	0.299 (0.304)	0.325 (0.266)	0.194	0.047	0.339 (0.269)	0.181 (0.547)	0.226	0.085	0.361 (0.232)	0.202 (0.494)
1990	0.538	0.454	0.345 (0.154)	0.519* (0.042)	0.595	0.521	0.522* (0.031)	0.391 (0.091)	0.458	0.359	0.288 (0.262)	0.504 (0.063)
2000	0.801	0.765	0.584** (0.003)	0.454* (0.013)	0.765	0.723	0.395* (0.037)	0.615** (0.004)	0.772	0.730	0.642** (0.002)	0.367* (0.047)
2010	0.778	0.738	0.829** (0.001)	0.084 (0.646)	0.820	0.788	0.670** (0.002)	0.327 (0.066)	0.805	0.770	0.871** (0.000)	0.043 (0.801)

* Coefficient is significant at the 0.05 level (two-tailed)

** Coefficient is significant at the 0.01 level (two-tailed)

greenspace locally. Without greenspace, the city-scale factor may be more influential because the intensified regional heat stress can overwhelm the local-scale factor. In 1990, the city-scale factor had a significant influence on the mean temperature in summer, which is in contrast to the importance of the local-scale factor for annual mean temperature (Table 5, 1990). This could be explained by the intensified heat stress in the city, where there could be greater heat accumulation and slower cooling in summer compared to other seasons. In particular, the heat stress could be more severe when there was less greenspace locally. Therefore, even if the city size was not large enough to impact the annual temperature, it could influence the summer temperature significantly. In 2000, the local-scale factor explained more variation of the mean temperature in summer, in contrast to the result for the mean temperature in winter and for the yearly average (Table 5, 2000). In this period, although the developed land increased at the local scale, the greenspace increased as well, which was a different land-cover trend compared to that of 1990. This may explain why during the heat-stressed season, the local-scale factor explained more than the city-scale factor. This suggests that the high temperature could be lowered in summer by local greening efforts. However, when the city size was very large, the city-scale factor became the overwhelming factor in all seasons (Table 5, 2010).

To mitigate the extreme heat, many recent studies focused on measurements at the local scale, including adding greenspace (Yue et al. 2007; Doick et al. 2014; Jenerette et al. 2015), changing building materials (Doulos et al. 2004; Steeneveld et al. 2011; Zinzi and Agnoli 2012; Santamouris 2013b; Kuang et al. 2015), and optimizing patterns of buildings or greenspace (Zhou et al. 2011; Li et al. 2012; Stewart and Oke 2012; Su et al. 2014). Results from this study indicate that the effectiveness of these measurements could be compromised by the increase of city size. As shown in this study, when the city size of Beijing approached 2000 km^2 in 2010, the city-scale factor was the only significant factor driving urban warming, and the local-scale factor was no longer significant, even with a large increase in the proportion of greenspace. These results suggest that a tipping point of city size may occur, within which the local regulations could be more effective to improve the thermal environment. However, this tipping point may vary by cities in different climates and urban structures, which warrants further research.

Limitations and future research

Most of the weather stations in the urban area of Beijing were frequently relocated. Therefore, here we only used the two urban stations that never relocated, Fengtai and Mentougou, to evaluate the overall magnitude of urban warming caused by urbanization. However, warming trends could be very different across the urban area due to different local environments (Böhm 1998). The warming trends of the two urban stations, Fengtai and Mentougou, are likely to represent the average magnitude in Beijing, weaker than those in the center area, and stronger than those of the remote towns. In fact, our results are similar to previous studies in Beijing (Liu et al. 2007; Ren et al. 2007; Yan et al. 2010).

We used 14 plain stations to study the relative importance of the local- and city-scale factors. With the expansion of Beijing city, the boundary of the city changed over time. For the outer-city stations that were close to the city boundary, they might become city stations due to the expansion. These changes, and whether to classify these stations into city stations may have slight influence on the magnitude of the city-scale impact, because we only had a limited number of stations (14 in total). Therefore, it is important to have a robust method in delineating the city boundary to determine the types of the weather stations in each period. For example, there were only four outer-city stations in 2010, so the influence at the city-scale might be overstated. However, when comparing to another study conducted in Beijing, in which 56 weather stations were used, we found our result, that is, the difference of 1.3 °C in annual mean temperature between city and outer-city stations in 2010, was very similar to that of 1.23 °C found in Yang et al. (2013).

In addition, at the local scale, we only considered the proportion of different land cover types, not the vertical structure of the landscape. The vertical structure, such as the building height, might change a lot during the period, and thus might have important effects on the local temperature. It would be interesting to include the vertical structure in future research, when data is available. At the city scale, it would be interesting to evaluate the relative importance of the physical extent and structure of the city, versus the increased anthropogenic heat due to urban sprawling in future studies.

Conclusion

Urbanization in the Beijing municipality significantly influenced trends of mean and minimum temperatures during the period from 1983 to 2011, and the warming trends were large even compared to other large or developing cities. Beijing city expanded with an increasing speed and differences in temperature between city and outer-city stations increased as well. The local developed land increased and showed significant correlations with air temperatures since 1990. The relative importance of the local- and city-scale factors contributing to the air temperature changed during urbanization and varied seasonally. When the city size was relatively small, the proportion of developed land at the local scale played a vital role in affecting air temperatures. However, in small cities, the city-scale factor would cause stronger heat stress in summer, if there were less local greenspace. With the increase of city size and local greenspace, the city-scale factor became more and more significant, but the local-scale factor was still important, especially in summer. However, when the size of the city became very large, even if there was much more greenspace at the local scale, the city-scale factor was the only factor that significantly influenced the air temperature. These results indicate that when a city is relatively small, optimizing the composition or configuration of land cover at the local scale could effectively alleviate some UHI effects. However, when the city is large, a more effective way is to control its sprawl and spatial extent. Results from this study enhance our understanding on how urban expansion and local land-cover change together affect urban warming, and provide insights for urban planning and management.

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