Spatiotemporal patterns of urban thermal environment and comfort across 180 cities in summer under China's rapid urbanization

Zhibin Ren [1], **Yao Fu** [1], **Yunxia Du** [Corresp., 1], **Hongbo Zhao** [Corresp. 2]

[1] Key Laboratory of Wetland Ecology and Environment, Northeast Institute of Geography and Agroecology,Chinese Academy of Sciences, Changchun, China

[2] Key Research Institute of Yellow River Civilization and Sustainable Development & Collaborative Innovation Center on Yellow River Civilization of Henan Province, Henan University, Kaifeng, China

Corresponding Authors: Yunxia Du, Hongbo Zhao
Email address: duyunxia@iga.ac.cn, 10340024@vip.henu.edu.cn

Background. China is considered as the largest and most rapidly urbanizing nation in the world. However, possible changes of urban thermal environment and comfort under the rapid urbanization in China still remain poorly understood at a national scale.

Methods. Based on the data collected from 180 cities in 1990, 2005, and 2015 in China, the spatiotemporal patterns of urban thermal environment and comfort in summer and their relationships with urbanization variables were investigated in this study.

Results. Our results indicate that urban thermal environment has changed greatly during the 25 years. Furthermore, the changes of urban climate in different regions are inconsistent. The Physiological Equivalent Temperature(PET) at most cities (81%) in China increased from 1990 to 2015, which suggested that urban thermal comfort in China was also deteriorating during the 25 years . However,while the PET of some cities in China began to decrease from 2005 to 2015, there were still 33% of cities that had positive trends,which mainly located in North region. Urbanization resulted in a significant influence on urban climate. Compared to southern cities, northern cities were more sensitive to urbanization impact. The most important contribution to increasing of PET for urbanization variables is Gross Domestic Product, followed by urban population. The analysis results reveal changing patterns of urban thermal comfort in China during summer season. It can help urban government and managers improve urban thermal environment and comfort.

Highlights

- Urban thermal environment and comfort has changed greatly during the last 25 years and such changes in different regions were inconsistent.
- From 1990 to 2015, the Physiological Equivalent Temperature (PET) of most cities (81%) in China exhibited an increasing trend, especially in North region (4℃), followed by Northeast region(3.4℃).
- From 2005 to 2015, the PET of some cities in China began to exhibit a decreasing trend. However, there were still 33% of cities,which exhibited positive trends and mainly located in North region.
- Urbanization has a significant influence on urban climate and the most important contribution to changes in urban thermal comfort is gross domestic product, followed by urban population.
- Our results reveal the spatiotemporal changing patterns of urban thermal comfort and can help urban planner to improve urban thermal environment in China.

Spatiotemporal patterns of urban thermal environment and comfort across 180 cities in summer under China's rapid urbanization

Zhibin Ren[1], Yao Fu[1] , Yunxia Du[1]* , Hongbo Zhao[2] *

[1]*Key Laboratory ofWetland Ecology and Environment, Northeast Institute of Geography and Agroecology,Chinese Academy of Sciences, Changchun 130102, China*

[2] *Key Research Institute of Yellow River Civilization and Sustainable Development & Collaborative Innovation Center on Yellow River Civilization of Henan Province, Henan University,Kaifeng 475001,China*

E-Mail:renzhibin1985@163.com (Z.Ren.); fuyao198704@163.com(Y. Fu.); duyunxia1985@163.com (Y.Du); 10340024@vip.henu.edu.cn (H.Zhao.)

**Corresponding author*: Tel:+86 431 85542321;Fax:+86 431 85542298

Abstract:

Background. China is considered as the largest and most rapidly urbanizing nation in the world. However, possible changes of urban thermal environment and comfort under the rapid urbanization in China still remain poorly understood at a national scale.

Methods. Based on the data collected from 180 cities in 1990, 2005, and 2015 in China, the spatiotemporal patterns of urban thermal environment and comfort in summer and their relationships with urbanization variables were investigated in this study.

Results. Our results indicate that urban thermal environment has changed greatly duringthe 25 years. Furthermore, the changes of urban climate in different regions are inconsistent. The Physiological Equivalent Temperature(PET) at most cities (81%) in China increased from 1990 to 2015, which suggested thaturban thermal comfort in China was also deteriorating during the 25 years . However,while the PET of some cities in China began to decrease from 2005 to 2015, there were still 33% of cities that had positive trends,which mainly located in North region. Urbanization resulted in a significant influence on urban climate. Compared to southern cities, northern cities were more sensitive to urbanization impact. The most important contribution to increasing of PET for urbanization variables is Gross Domestic Product, followed by urban population. The analysis results reveal changing patterns of urban thermal comfort in China during summer season. It can help urban government and managers improve urban thermal environment and comfort

Key words: Urban Climate; Physiological Equivalent Temperature (PET); Thermal comfort; Urbanization

1.Introduction

Many parts in the world have experienced the rapid urbanization during last few decades (Montgomery,2017; Szabo, 2018). The expansion of urban impervious surfaces can especially change urban thermal environment, which makes significant impacts on urban life quality and even urban sustainable development (Cao et al.,2018; Lin et al.,2018). The high urban temperature and intensive heat can result in high cooling energy consumption (Giridharan et al.,2018; Kolokotroni et al.,2007), raise pollution levels (Sarrat et al.,2006; Weng and Yang,2006) , reduce urban thermal comfort (UTC)(Basu and Samet,2002; Klenk et al.,2010; Salata et al., 2014), decrease outdoor activities and cause serious public health problems (Wong et al.,2018 ; Sagris et al.,2018). The urban thermal environment may be expected to become worse in the coming years with two significant escalating global trends (urban heat islands(UHI) and global warming). Therefore, a thorough understanding of urban thermal environmental patterns is critical for urban planners to adapt effective mitigation measures and strategies to improve urban thermal environment, especially in summer time.

Urban thermal environmental issues have recognized by scientists and urban planners during the past several decades. Previous studies on the urban thermal environment have relied on land surface temperature extracted from remote sensing (e.g., Weng et al.,2007; Cao et al.,2010; Lin, 2018) and air temperature observed at weather station (e.g., Shereif et al., 2018; Oxoli et al., 2018; Wang et al., 2018). The urban temperature has been the most intuitive performance indicator for analyzing the urban thermal environment (Lan et al.,2017; Moustris et al.,2018). However, the urban air temperature is an inadequate measure to investigate urban thermal environment (Aljawabra et al.,2018; Cheung et al.,2018). Moreover, urban thermal

comfort is a state of mind that articulates satisfaction with a specific urban thermal environment, depending on a combined effect of the physical and climatic parameters(Aljawabra et al.,2018; Galagoda et al.,2018).When analyzing the urban thermal environment, it is important to bear in mind that the other factors could also influence urban thermal environment such as solar radiation, humidity, and wind speed besides the air temperature(Lee et al.,2018; Yang et al.,2018). Therefore, the urban thermal comfort can better render the implication of the urban thermal environment because it considers an integral effect of climatic parameters, such as, air temperature, wind speed, air humidity and solar radiation (Salata et al.,2017). When urban residents are under more thermal stress, an urban accompanying discomfort could negatively affect their outdoor life and health in many ways (Salata et al.,2017;Cao et al.,2018). Therefore, a better understanding and monitoring of the urban thermal comfort is necessary and important for developing strategies for urban planners, and policy makers to mitigate urban thermal stress and improve urban life quality in cities.

China as a developing country has experienced a rapid urbanization in the past six decades. In China, some studies showed that urbanization has contributed greatly to the observed warming since the 1960s (Tarabon et al.,2018;Wang et al., 2019). By 2030, urban dwellers in China will increase by nearly 200 million (Wu et al., 2014), which will further exacerbate urban warming stress on humans. However, how the urban thermal comfort changes in China under the rapid urbanization is not well understood yet. Furthermore, most previous efforts about urban thermal comfort just focused on several selected measurements by using conventional meteorological monitoring approaches in a single city or a few big cities (e.g., Lindén et al.,2016;Cheung et al.,2018; Xu et al.,2018). This may not only understand the thermal comfort in single cities, but also fail to reveal the detailed patterns of urban thermal comfort at a national scale (Huang et al.,2016; Zhou et al., 2018). Spatiotemporal patterns of urban thermal comfort under the rapid urbanization in China are still poorly understood at the national scale. Therefore, more detailed studies on nationwide cities and across different climatic zones are needed. The better understanding of spatiotemporal change of urban thermal comfort is imperative today especially

123 when China is constrained by both urbanization and global climate change.

124 In this study, based on long-term daily meteorological observations and urbanization
125 information collected from the Statistics Yearbook of Cities in 1990, 2005, to 2015 in 180 cities
126 of China, we propose to analyze spatiotemporal patterns of urban thermal environment and
127 comfort in the cities. More specific research objectives include: (1) to investigate
128 spatiotemporal changes of urban climate under a rapid urbanization in 1990, 2005 and 2015, (2)
129 to explore the spatiotemporal changes of urban thermal comfort in the 180 cities in summer
130 under the rapid urbanization,and (3) to analyze relationships between thermal comfort index
131 and urbanization factors. The expected research results would be helpful for better understanding
132 of relationships between urbanization and urban thermal comfort and provide useful information
133 to urban government and planner to improve urban thermal environment.

134 # 2.Methods

135 ## 2.1. Study areas

136 In our study, the 180 cities under rapidly urbanizing process were selected due to the
137 availability of relevant meteorological and urbanization data in China (Fig.1). The administrative
138 boundary of cities in China often includes very large areas of countryside. In this study, only the
139 built-up area of each city was analyzed, without considering the whole area within the
140 administrative boundary. The built-up area refers to the urbanized area of a city (National Bureau
141 of Statistics of China, 1990–2010). In order to explore regional patterns in urban thermal
142 environment, the selected cities in our study were then divided into seven different regions
143 (Northeast, North, South, Northwest, Southwest, Central and East), according to regional
144 division criterion used by the national government(Zhao et al.,2013). These seven regions
145 include all the provinces of mainland China.
146 |Insert Fig. 1 around here|

147 **2.2. Data collection**

148 **Meteorological data**: Given the long-term meteorological observation data from 1980
149 to2016, we found that there were not extreme climatic events occurring in years 1990, 2005 and
150 2015 and the climate in 1990, 2005, and 2015 could almost represent the average climatic
151 condition of 1990s, 2000s, and 2010s (Table.1). Therefore, the historical publicly available
152 meteorological data observed in 1990, 2005 and 2015 from the National Meteorological
153 Information Center (http://data.cma.cn/) were used in our study in order to investigate
154 spatiotemporal trends of urban thermal comfort. The monthly meteorological parameters
155 observed in summer months (June, July and August) used in this study included monthly average
156 values of air temperature, relative humidity, wind velocity and global radiation. For every city,
157 all meteorological parameters observed from all the Chinese surface meteorological stations in
158 urban built-up area were used in our study and such kind of data has been widely used to study
159 the urban thermal environment (e.g., Han et al.,2019; Liu et al., 2019; Yang et al., 2019). The
160 four variables from the meteorological stations in June, July and August were also averaged
161 into the summer season. Our focus is on the summer season because hundreds of millions of
162 urban residents in China endure their highest heat-related stress during the time period of a year.
163 **Urbanizaiton data**: all the data of urbanization variables were collected from the Statistics
164 Yearbook of Cities in China (National Bureau of Statistics of China, 1990–2016). This series of
165 yearbooks has been compiled and published annually by the National Bureau of Statistics since
166 1985. The document data published in each yearbook in a given year were from the previous
167 year. The yearbooks published between 1991 and 2016 were used to collect data for the 25 years
168 between 1990 and 2015. Urbanization is a process marked by urban area expansion with
169 intensive land use change, economic development, and rapid population growth (Antrop, 2000;
170 Weber and Puissant, 2003). Therefore, all the continuously recorded variables related to
171 population, land cover and economic development were used to analyze urbanization impact on
172 urban thermal environment in our study. There were six variables that were defined or
173 calculated according to the official statistical yearbooks(National Bureau of Statistics of China,

1991–2016), including total urban population, urban population in build-up area, built-up area(km^2), population density(n/km^2), GDP(10^8 Yuan), per capita GDP(Yuan/person) and urban vegetation coverage (%).

2.3. Calculation of Urban thermal comfort

Physiological Equivalent Temperature (PET) is one of the most regularly used thermal comfort index to assess the human thermal condition, which has been widely applied in different climatic zones (Potchter et al. 2018). PET is based on human energybalance in terms of the Munich Energy Balance Model for individuals (Matzarakis et al.2013). It is a universal index which integrates the thermo-physiology of the human body (sex, height, activity, clothing resistance for heat transfer,shortwave albedo and long wave emissivity of the surface) and the multiple relevant meteorological parameters including air temperature, relative humid, wind velocity etc. PET is derived from the human energy balance and expressed in the unit (℃) as an indicator of thermal stress, which makes the result more comprehensible for urban and regional planners, decision-makers, and even the public (Froehlich et al.2018). Based on the monthly average values of air temperature, relative humidity, wind velocity and global radiation for summer in 1990, 2005,and 2015 in this study, the monthly PET index for urban stations for every city in June, July and August was calculated by RayMan software (Matzarakis et al. 2007, 2010). The thermos-physiological parameters of the human beings used in this research were set up as a typical male 35 years old, 1.75 m height, 75 kg weight, with an internal heat production of 80 W and a heat transfer resistance of the clothing of 0.9 clo. The assessment scale used in this study to classify cold stress (PET < 13 ◦ C), thermal comfort (13 ⩽ PET ⩽ 29) and heat stress (PET > 35 ◦ C) is described in Table 2.

|Insert Table 2 around here|

2.4 Data analysis

The values of the PET in June, July and August for urban stations in each city were first averaged into a summer PET for all following analyse. Based on the values of summer PET in

1990, 2005, and 2015, spatial change patterns of PET among the three years in different regions in China were then conducted in our study.

By analyzing the distribution of urbanization variables, we found that that GDP, per capita GDP, built-up area, total population, population density, population in the built-up area had a highly skewed distribution. Therefore, these variables were in-transformed before correlation and regression analyse in order to improve the comparability and the linearity of relationships between PET and a set of urbanization variables. In order to analyze the impact of urbanization on PET, the research on the relationship between PET and urbanization variables was conducted. First, the Pearson correlation analysis and correlation coefficient were conducted between these independent and dependent variables. Second, a simple linear regression model was used to determine the effect of urbanization on PET. In our analysis, these six urbanization variables in the selected three years (1990, 2005, and2015) were used as independent variables and the corresponding average PET was used as a dependent variable. As most variables were significantly correlated with each other, we finally conducted a multiple regression analysis in which PET was the response variable and urbanization variables were predictors. All statistical analyses were carried out by using SPSS19.0.

3. Results

3.1. Spatiotemporal changes of urbanization and meteorological parameters in China

Per the seven variables of urbanization in China, the statistical results showed that China experienced a rapid urbanization during the last 25 years (1990-2015) (Table.3). Compared to 45.4 km^2 in 1990, the mean urban build-up area reached to 117.9 km^2 and 160.2 km^2 in 2005 and 2015 respectively. Urban population and GDP increased greatly from 1990, 2005 to 2015. During the last 25 years, urban vegetation coverage also increased sharply (Table.3).

|Insert Table 3 around here|

Due to the rapid progress of urbanization such as land cover change and the increasement of

urban population over China, urban thermal parameters, such as, air temperature, humidity, wind speed, solar radiation parameters could correspondingly be changed correspondingly. The average air temperature increased significantly from 1990 to 2005 and decreased slightly from 2005 to 2015 (Table 3). Analysis of the average value of air temperature in different regions (Fig.2) indicated that different changes have occurred across different regions from 1990 to 2015. The air temperature in Northeast and Northwest increased gradually from 1900, 2005 to 2015. However, it decreased from 1990 to 2015 in Central and East China. The relative humidity and wind speed showed significant decreasing changes, especially in Northeast, North, and Northwest regions.

|Insert Fig. 2 around here|

3.2. Spatiotemporal changes of PET across 180 cities in hot summer

The average PET increased significantly from 1990 to 2015(Table 4), which means people suffer from more and more heat stress during the summer period and feel extremely uncomfortable. For the 180 cities in 1990, the PET ranged from 13.2℃ to 34.3℃ with an average of 28.7℃. The urban average PET reached up to 31.7℃with an increase rate of 11% from 1990 to 2005. Compared to the average PET in 2005, it slightly decreased in 2015 with the average value of 30.6℃. Analysis of the average value of PET in all different regions in mainland China showed that cities in the South region had the highest level of PET with 33.5℃, followed by the Central region. The lowest levels of PET have occurred in Northeast and Northwest region with only 27℃(Fig. 3). The frequency analysis of PET in 180 cities (Fig .4) indicated showed that the highest frequency for PET between 29 and 35 was 60% (Moderate heat stress) in 1990 and it increased gradually to 63% in 2005, and 70% in 2015. Meanwhile, the frequency for PET between 18 and 23 (No thermal stress) decreased gradually from 8% in 1990 to 0.55% in 2015.

|Insert Table 4 and Figs. 3 & 4 around here|

From 1990 to 2005, the PET of most cities in China exhibited an increasing change (Fig. 5-6). Of the 180 cities investigated, ninety-five percent of them had positive change values, ranging from 0.1℃ to 6.8℃ (Fig. 5-6) and 80% of the values were larger than 1.5℃, with a highest rate of increase occurring in North region (4℃), followed by Northeast region(3.4℃). From 2005 to 2015, the PET in some cities in China began to exhibit a decreasing change (Fig. 6). Sixty-seven percent had negative change values, especially in South region. However, there are still 33% of cities had positive values ,mainly located in North region (Fig. 6-7). Overall, the PET of most cities (81%) in China exhibited an increasing change (Fig. 6-7) from 1990 to 2015.

|Insert Figs. 5 - 7 around here|

3.3.Effect of urbanization on PET in hot summer in China

Table 5 lists the Pearson's correlations between PET and urbanization variables. Five of the seven urbanization variables had significant positive effects on PET except for population density. Meanwhile, urban vegetation coverage had a negative relationship with PET. In addition, the increase 1 in Ln(GDP) resulted in an increase of 0.67 for PET (Fig. 7). The increase 1 in Ln(total population) lead to an increase of 0.61 for PET. From the R^2 value in Fig 7, we can easily see that the variables of GDP and total population could explain 22.0% and13.2% of variance of PET, respectively. Finally the multiple regression analysis showed a constructed model using the four most significant variables as follows:

$y = -25.759 + _1.256b_1 - 2.036b_2 + 1.104b_3 + 0.051b_4$

where y is the green space coverage and b1-4 are the variables shown in Table 6. This model explained 31.6.7% of the variance of PET.

|Insert Tables 5 & 6 around here|

4. Discussion

China has experienced the rapid urbanization during the last 30 years (Jiang et al.,2019; Lu

et al.,2019), which could definitely cause changes of urban climate. The warming change caused by urbanization has already been well-documented (e.g., Lin et al.,2018; Fu et al.,2018; Yang et al.,2019). Our results have also agreed to those existing studies , which showed that the average air temperature increased significantly from 1990 to 2005 and to 2015. Such increasing changes may be linked to appearances of increasing impervious surfaces during the rapid urbanization progress. The greater absorption capacity of solar radiation, heat capacity and conductivity in the urban area, resulted in more heat storage (Zhang et.al, 2019), which leads to a substantial increase in sensible heat flux during daytime and heat release at night. Our studies also demonstrated showed that the relative humidity appeared the significant decreasing changes, which might be caused by huge losses of leaf area index, green vegetation fraction, and so on because of urban sprawl and land use and land cover change) (LULC) (Hernandez-Moreno et al.,2018; Sun et al.,2018). In addition,the mean wind speed for 180 cities also showed significant decreasing changes from 1990 to 2005, and to 2015. The surface roughness over urban region was significantly altered because of the emergence of high-rise buildings and other LULCC(Walker,2011; Anup et al.,2019), which caused surface drag force increases and then decreased the wind speed in cities.

In recent years, many studies have only used single-climate parameters, such as, air temperature (Ta), to serve as indicators of urban thermal environment (Weng et al.,2007;Shereif et al., 2018; Oxoli et al., 2018). In fact, the temperature factor only could not represent adequately urban thermal environment. Urban thermal comfort could better represent urban thermal environment because of consideration of the integral effect of the climatic parameters of the air temperature, wind speed, air humidity and solar radiation (Salata et al.,2017). Our results indicated that the PET of most cities (81%) in China exhibited a great increasing change (Fig. 3-4) from 1990 to 2015. The impact of urbanization on temperature and thermal comfort is quite different among the different cities and regions in China. Our research also indicated that the PET changes were much larger than air temperature changes associated with urban thermal conditions. This is because that urbanization has a negative impact on relative humid and wind

velocity in urban area in addition to the warming change. Therefore, thermal comfort should be a better indicators to characterize the urban thermal environment than the urban air temperature.

In addition, our results also showed that cities in the South region had the highest level of PET (33.5), followed by the Central region and Northeast and Northwest region with only 27℃(Fig. 3), which could be closely linked with the different regional climates. Many studies found that the higher temperature and humidity over China during summer is mainly distributed in the southeast of China, and relatively lower temperature and humidity concentrates in the western and northern of China, which may cause the different regional patterns of PET (e.g., Li and Zha.,2018; Yao et al.,2017; Peng et al.,2018). Our results furtherly indicated that the change of PET also exhibits a regional characteristic, suggesting larger increasing trends occurring in Northeast and North China from 1990 to 2005, and to 2015 and some decreasing trends in South regional cities from 2005 to 2015 (Fig. 5-6). There may be several reasons for the spatial inconsistent changes of urban thermal comfort in these cities, which maybe closely related with the different processes of urbanization in different regions in China. The economic development in the north is dominated by heavy industries characterized with high energy consumption (Zhang et al.,2019; Pan et al.,2019). The average summer temperatures in Northeast and North regions could be increased greatly by waste heat released by secondary industry. Therefore, PET in the cold northeastern China is more susceptible to the impact of urbanization. However, the economic development in the south is dominated by light industries characterized with high technology(Wu et al.,2019; Liu et al.,2019). Many cities in South region have higher environmental efficiencies than those northeastern cities. Some regulations of reforming technology or other measures like recycling wastes intensively and subsidizing the sewage disposal plants in recent years play an important role in reducing emissions (Ma et al.,2019). Therefore, the PET increased slower in north regions from 1990 to 2005 and even decreased from 2005 to 2015 than that in south regions. It might also be because that China has put ecological civilization as a national strategy to build a beautiful China in recent years(Shi et al.,2019; Geall et al.,2018). This strategy became a great opportunity for urban forest

development in China. The government strengthens the building of China's urban forest. Urban forest amounts and quality also have been further improved, especially for south regions ,which has improved urban thermal environment to a certain extent (Liu et al.,2018).

Most of the previous studies analyzed relationships between urban air temperature and its drivers across cities over time (Lin et al.,2018; Fu et al.,2018; Yang et al.,2019). The correlation analyses between PET and associated drivers can be conducted across space and time(Yang et al.,2019; Cao et al.,2018). In this study, we performed correlation analyses across both cities and years, and a series of new and different findings were revealed. In this study, increased GDP and population might be an important reason for the increased PET (Table 4-5). The increasing GDP and population due to the urbanization might result in decreasing the vegetation coverage, and increasing amounts of roads and buildings and energy consumption(Hernandez-Moreno et al.,2018;Sun et al.,2019), and thus increasing the PET indirectly. The growing concentration of GDP and population is the most basic connotation of urbanization, The secondary sector of the economy for GDP includes that industries consume large quantities of energy and require factories and machinery to convert the raw materials into goods and products and produce waste heat that may cause thermal environmental problems(Wu et al.,2019; Zhang et al., 2019). Besides, the heat generated by human body and people's daily life, such as, air conditions and cars, has also caused the increasing artificial heat emissions (Liu et al.,2018; Ma et al.,2019;) and thereby affected people's thermal comfort. Our results indicated that the correlation between urban vegetation coverage and PET is not significant. However, many previous studies demonstrated that vegetation coverage has a remarkable impact on regional climate (e.g., Zhao et al.,2014; Alo et al.,2010; Chen et al.,2017). It might be because that urban vegetation was scattered and heterogeneous, surrounded by many impervious surfaces, which could reduce the ecological function of vegetation, such as, decreasing temperature and increasing humidity, etc (Ren et al.,2018; Wang et al.,2019). Besides, urban vegetation amount is relatively small compared with natural vegetation.

Undeniably, there exist some limitations for our research. It should be noted that PET

intensity was obtained by only three years (1990, 2005, and 2015) for summer in our research. The PET in more continuous years should be used to conduct the spatiotemporal change patterns of urban thermal environment.In addition, PET might not change significantly in cities over years, especially when averaged into a single season Our study did not capture the severity of urban thermal discomfort and neither its peaks, and the averaged PET for a summer season might only provide a general condition for each city in each year. Therefore, more temporal studies should be conducted to explore the daily variation of PET in the future to reveal some more detailed information about PET(Ren et al.,2018). Besides, the correlation analyses conducted in different regions may lead to different results according to previous studies(Lin et al.,2018; Cao et al.,2018; Sun et al.,2019;). Therefore, there are some limitations existing in the correlation analyses across different regions. For comprehensive understanding relationships between PET and drivers, it is necessary to analyze the relationships across different regions. However, if we would like to accurately identify the associated drivers and mitigation strategies of PET in single city, it is better to analyze the relationships between PET and its drivers across many continuous years.

Given the general circumstance of global climate warming, the frequency and intensity of urban heat events would increase, especially in developing countries such as China (Sun et al.,2019) and urban thermal environment could be deteriorated in the future. Our study presented here will have some great management implications with many benefits to the urban planning, healthcare organizations and the power sector. Existing research has showed that the increase of urban air temperature could result in more usage of electricity (Akbari, Pomerantz, & Taha, 2001; Limones-Rodriguez et al.,2018). Our study results could provide the basic information associated with the urban thermal environment to city power agencies. The spatiotemporal patterns of summer PET intensity could help the power agencies get the power demand variability at different cities. In addtion, many cities are aggressively taking some measures such as cool/green roofs and urban greening to reduce the urban heat island phenomena and moderate urban thermal environment (e.g., Akbari, Konopacki, & Pomerantz,1999; Lai et al.,2019).

Information on monthly and seasonal changes of urban thermal comfort could help these governmental agencies quantify the potential benefits of various adaptation strategies.

5. Conclusions

Rapid urbanization has a great impact on urban thermal environment. In this study, we conducted the analysis of changing patterns of urban thermal environment and comfort for 180 cities in China over the past 25 years and attempted to explore relationships between urbanization variables and urban thermal comfort. By this study, several conclusions may be derived from our experimental results as follows:

(1) Urban thermal environment and comfort has changed greatly during the 25 years and the changes of urban climate in different regions are inconsistent.

(2) From 1990 to 2015, the PET of most cities (81%) in China exhibited an increasing change, especially in North region (4℃), followed by Northeast region(3.4℃). From 2005 to 2015, the PET in some cities in China began to exhibit decreasing changes. However, there are still 33% of cities that had positive trends, mostly occurring in North region in China.

(3) Urbanization has a significant influence on urban climate and five of the seven urbanization variables presented significant positive effects on PET except for population density. The most important contribution to changes in thermal comfort is GDP, followed by urban population.

Changes in urban thermal environment caused by urbanization need to be emphasized seriously, especially the cities in the Northeast and North region in China. Our results may help researchers and city planners to well understand PET formation and provide practical guidelines, such as, reasonable planning for an unbalanced regional development of industries for urban planners to improve urban thermal environment. .

Acknowledgements

This research was supported by Youth Science fund project (41701210) sponsored by the National Natural Science Foundation of China and Science Development Project of Jilin

Province, China (20180418138FG). We would like also to provide our great gratitude to the editors and the anonymous reviewers who gave us their insightful comments and suggestions.

References

Aljawabra, F, Nikolopoulou, M (2018) Thermal comfort in urban spaces: a cross-cultural study in the hot arid climate. International Journal of Biometeorology 62:1901-1909.

Alo, C, Wang, G, (2010) Role of dynamic vegetation in regional climate predictions over western Africa. Climate Dynamics 35: 907-922.

Anup, K C, Whale, J, Urmee, T (2019) Urban wind conditions and small wind turbines in the built environment: A review. Renewable Energy 131:268-283.

Basu, R, Samet, J M (2002) Relation between elevated ambient temperature and mortality: A review of the epidemiologic evidence. Epidemiologic Reviews 24:190-202.

Cao, Q, Yu, D, Georgescu, M, Wu, J, Wang, W (2018) Impacts of future urban expansion on summer climate and heat-related human health in eastern China. Environment International 112:134-146.

Cao, X, Onishi, A, Chen, J, Imura, H (2010) Quantifying the cool island intensity of urban parks using ASTER and IKONOS data. Landscape and Urban Planning 96:224-231.

Cheung, P K, Jim, C Y (2018) Subjective outdoor thermal comfort and urban green space usage in humid-subtropical Hong Kong. Energy and Buildings 173:150-162.

Chen, L, Ma, Z, Zhao, T, (2017) Modeling and analysis of the potential impacts on regional climate due to vegetation degradation over arid and semi-arid regions of China. Climatic Change 144: 461-473.

Froehlich, D, Matzarakis, A (2018). Spatial Estimation of Thermal Indices in Urban Areas-Basics of the SkyHelios Model. Atmosphere 9:1-6.

Fu, P, Weng, Q (2018) Variability in annual temperature cycle in the urban areas of the United States as revealed by MODIS imagery. Isprs Journal of Photogrammetry and Remote Sensing 146:65-73.

434 Galagoda, R U, Jayasinghe, G Y, Halwatura, R U, Rupasinghe, H T (2018) The impact of urban
435 green infrastructure as a sustainable approach towards tropical micro-climatic changes and
436 human thermal comfort. Urban Forestry & Urban Greening 34:1-9.
437 Geall, S, Ely, A (2018) Narratives and Pathways towards an Ecological Civilization in
438 Contemporary China. China Quarterly 236:1175-1196.
439 Giridharan, R, Emmanuel, R (2018) The impact of urban compactness, comfort strategies and
440 energy consumption on tropical urban heat island intensity: A review. Sustainable Cities
441 and Society 40:677-687.
442 Han, S, Tang, Q, Xu, D (2019) Impacts of urbanization and agricultural development on
443 observed changes in surface air temperature over mainland China from 1961 to 2006.
444 Theoretical and Applied Climatology 135: 3-4.
445 Hernandez-Moreno, A, Reyes-Paecke, S (2018) The effects of urban expansion on green
446 infrastructure along an extended latitudinal gradient (23 degrees S-45 degrees S) in Chile
447 over the last thirty years. Land Use Policy 79:725-733.
448 Huang, J, Zhou, C, Zhuo, Y, Xu, L, Jiang, Y (2016) Outdoor thermal environments and activities
449 in open space: An experiment study in humid subtropical climates. Building and
450 Environment 103:238-249.
451 Jiang, S, Hua, H, Sheng, H, Jarvie, H P, Liu, X, Zhang, Y, Yuan, Z, Zhang, L, Liu, X (2019)
452 Phosphorus footprint in China over the 1961-2050 period: Historical perspective and future
453 prospect. Science of the Total Environment 650:687-695.
454 Klenk, J, Becker, C, Rapp, K (2010) Heat-related mortality in residents of nursing homes. Age
455 and Ageing 39:245-252.
456 Kolokotroni, M, Zhang, Y, Watkins, R (2007) The London Heat Island and building cooling
457 design. Solar Energy 81:102-110.
458 Lai, D, Liu, W, Gan, T, Liu, K, Chen, Q (2019) A review of mitigating strategies to improve the
459 thermal environment and thermal comfort in urban outdoor spaces. The Science of the total
460 environment 661:337-353.

461 Lan, Y, Zhan, Q (2017) How do urban buildings impact summer air temperature? The effects of
462 building configurations in space and time. Building and Environment 125:88-98.
463 Lee, H, Mayer, H (2018) Thermal comfort of pedestrians in an urban street canyon is affected by
464 increasing albedo of building walls. International Journal of Biometeorology 62:1199-1209.
465 Li, L, Zha, Y,(2018) Mapping relative humidity, average and extreme temperature in hot
466 summer over China. Science of the Total Environment 615: 875–881.
467 Limones-Rodriguez, N, Marzo-Artigas, J, Fernanda Pita-Lopez, M, Pilar Diaz-Cuevas, M (2018)
468 The impact of climate change on air conditioning requirements in Andalusia at a detailed
469 scale. Theoretical and Applied Climatology 134:1047-1063.
470 Lin, L, Ge, E, Liu, X, Liao, W, Luo, M (2018a). Urbanization effects on heat waves in Fujian
471 Province, Southeast China. Atmospheric Research 210:123-132.
472 Lin, Y, Jim, C Y, Deng, J, Wang, Z (2018b) Urbanization effect on spatiotemporal thermal
473 patterns and changes in Hangzhou (China). Building and Environment 145:166-176.
474 Linden, J, Fonti, P, Esper, J (2016) Temporal variations in microclimate cooling induced by
475 urban trees in Mainz, Germany. Urban Forestry & Urban Greening 20:198-209.
476 Liu, C, Chen, L, Vanderbeck, R M, Valentine, G, Zhang, M, Diprose, K, McQuaid, K (2018) A
477 Chinese route to sustainability: Postsocialist transitions and the construction of ecological
478 civilization. Sustainable Development 26:741-748.
479 Liu, Z, Liu, Y, He, B-J, Xu, W, Jin, G, Zhang, X (2019) Application and suitability analysis of
480 the key technologies in nearly zero energy buildings in China. Renewable & Sustainable
481 Energy Reviews 101:329-345.
482 Liu, Q, Peng, Pei, Wang, Y (2019) Microclimate regulation efficiency of the rural homegarden
483 agroforestry system in the Western Sichuan Plain, China. Journal of Mountain Science 16:
484 516-528.
485 Lu, X, Lin, C, Li, W, Chen, Y, Huang, Y, Fung, J C H, Lau, A K H (2019) Analysis of the
486 adverse health effects of PM2.5 from 2001 to 2017 in China and the role of urbanization in
487 aggravating the health burden. Science of the Total Environment 652:683-695.

488 Ma, M, Cai, W, Wu, Y, 2019. China Act on the Energy Efficiency of Civil Buildings (2008) A
489 decade review. Science of the Total Environment 651:42-60.
490 Mahmoud, S H, Gan, T Y (2018) Long-term impact of rapid urbanization on urban climate and
491 human thermal comfort in hot-arid environment. Building and Environment 142:83-100.
492 Matzarakis, A, Mayer, H, Iziomon, M G (1999) Applications of a universal thermal index:
493 physiological equivalent temperature. International Journal of Biometeorology 43:76-84.
494 Matzarakis, A, Rammelberg, J, Junk, J (2013) Assessment of thermal bioclimate and tourism
495 climate potential for central Europe-the example of Luxembourg. Theoretical and Applied
496 Climatology 114:193-202.
497 Montgomery, M (2017) Population Growth and Rapid Urbanization in the Developing World.
498 Population and Development Review 43:176-177.
499 Moustris, K, Tsiros, I X, Tseliou, A, Nastos, P (2018) Development and application of artificial
500 neural network models to estimate values of a complex human thermal comfort index
501 associated with urban heat and cool island patterns using air temperature data from a
502 standard meteorological station. International Journal of Biometeorology 62:1265-1274.
503 Oxoli, D, Ronchetti, G, Minghini, M, Molinari, M E, Lotfian, M, Sona, G, Brovelli, M A (2018)
504 Measuring Urban Land Cover Influence on Air Temperature through Multiple Geo-Data-
505 The Case of Milan, Italy. Isprs International Journal of Geo-Information 7.
506 Pan, S-Y, Gao, M, Shah, K J, Zheng, J, Pei, S-L, Chiang, P-C (2019) Establishment of enhanced
507 geothermal energy utilization plans: Barriers and strategies. Renewable Energy 132:19-32.
508 Peng, J, Ma, J, Liu, Q, Liu, Y, Hua, Y, Li, Y, (2018) Spatial-temporal change of land surface
509 temperature across 285 cities in China: An urban-rural contrast perspective. Science of the
510 Total Environment 635:487–497.
511 Potchter, O, Cohen, P, Lin, T-P, Matzarakis, A (2018) Outdoor human thermal perception in
512 various climates: A comprehensive review of approaches, methods and quantification.
513 Science of the Total Environment 631-632:390-406.
514 Ren, Z, He, X, Pu, R,(2018)The impact of urban forest structure and its spatial location on urban

515 cool island intensity.Urban Ecosystems 21: 863-874.
516 Sagris, V, Sepp, M (2017) Landsat-8 TIRS Data for Assessing Urban Heat Island Effect and Its
517 Impact on Human Health. Ieee Geoscience and Remote Sensing Letters 14:2385-2389.
518 Salata, F, Golasi, I, Ciancio, V, Rosso, F (2018) Dressed for the season: Clothing and outdoor
519 thermal comfort in the Mediterranean population. Building and Environment 146:50-63.
520 Salata, F, Golasi, L, Petitti, D, Vollaro, E d L, Coppi, M, Vollaro, A d L (2017) Relating
521 microclimate, human thermal comfort and health during heat waves: An analysis of heat
522 island mitigation strategies through a case study in an urban outdoor environment.
523 Sustainable Cities and Society 30:79-96.
524 Sarrat, C, Lemonsu, A, Masson, V, Guedalia, D (2006) Impact of urban heat island on regional
525 atmospheric pollution. Atmospheric Environment 40:1743-1758.
526 Shi, F, Weaver, D, Zhao, Y, Huang, M-F, Tang, C, Liu, Y (2019) Toward an ecological
527 civilization: Mass comprehensive ecotourism indications among domestic visitors to a
528 Chinese wetland protected area. Tourism Management 70:59-68.
529 Sun, R, Lu, Y, Yang, X, Chen, L (2019) Understanding the variability of urban heat islands from
530 local background climate and urbanization. Journal of Cleaner Production 208:743-752.
531 Sun, X, Crittenden, J C, Li, F, Lu, Z, Dou, X (2018) Urban expansion simulation and the spatio-
532 temporal changes of ecosystem services, a case study in Atlanta Metropolitan area, USA.
533 Science of the Total Environment 622:974-987.
534 Sun, Q, Miao, C, Hanel, M, Borthwick, A. G, Duan, Q, Ji, D, & Li, H (2019). Global heat stress
535 on health, wildfires, and agricultural crops under different levels of climate warming.
536 Environment international 128: 125-136.
537 Szabo, C P (2018) Urbanization and mental health: a developing world perspective. Current
538 Opinion in Psychiatry 31:256-257.
539 Tarabon, S, Bertrand, R, Lavoie, C, Vigouroux, T, Isselin-Nondedeu, F (2018) The effects of
540 climate warming and urbanised areas on the future distribution of Cortaderia selloana,
541 pampas grass, in France. Weed Research 58:413-423.

542 Wang, K, Li, Y, Luo, Z, Yin, S, Chan, P W (2018) Harmonic analysis of 130-year hourly air
543 temperature in Hong Kong: detecting urban warming from the perspective of annual and
544 daily cycles. Climate Dynamics 51:613-625.
545 Wang, Y, Chen, L, Song, Z, Huang, Z, Ge, E, Lin, L, Luo, M (2019) Human-perceived
546 temperature changes over South China: Long-term trends and urbanization effects.
547 Atmospheric Research 215:116-127.
548 Wang, W, Zhang, B, Zhou, W, (2019)The effect of urbanization gradients and forest types on
549 microclimatic regulation by trees, in association with climate, tree sizes and species
550 compositions in Harbin city, northeastern China. Urban Ecosystems 22: 367-384.
551 Weng, Q, Liu, H, Lu, D (2007) Assessing the effects of land use and land cover patterns on
552 thermal conditions using landscape metrics in city of Indianapolis, United States. Urban
553 Ecosystems 10:203-219.
554 Weng, Q, Yang, S (2006) Urban air pollution patterns, land use, and thermal landscape: An
555 examination of the linkage using GIS. Environmental Monitoring and Assessment 117:463-
556 489.
557 Wong, L P, Alias, H, Aghamohammadi, N, Aghazadeh, S, Sulaiman, N M N (2018) Physical,
558 Psychological, and Social Health Impact of Temperature Rise Due to Urban Heat Island
559 Phenomenon and Its Associated Factors. Biomedical and Environmental Sciences 31:545-
560 550.
561 Wu, J (2014) Urban ecology and sustainability: The state-of-the-science and future directions.
562 Landscape and Urban Planning 125:209-221.
563 Wu, Y, Tam, V W Y, Shuai, C, Shen, L, Zhang, Y, Liao, S (2019) Decoupling China's economic
564 growth from carbon emissions: Empirical studies from 30 Chinese provinces (2001-2015).
565 Science of the Total Environment 656:576-588.
566 Xu, M, Hong, B, Mi, J, Yan, S (2018) Outdoor thermal comfort in an urban park during winter in
567 cold regions of China. Sustainable Cities and Society 43:208-220.
568 Yang, Q, Huang, X, Tang, Q (2019) The footprint of urban heat island effect in 302 Chinese

569 cities: Temporal trends and associated factors. Science of the Total Environment 655:652-
570 662.
571 Yang, W, Lin, Y, Li, C-Q (2018) Effects of Landscape Design on Urban Microclimate and
572 Thermal Comfort in Tropical Climate. Advances in Meteorology. 28:1-13
573 Yang, X, Yao, L,Peng, LH (2019) Evaluation of a diagnostic equation for the daily maximum
574 urban heat island intensity and its application to building energy simulations. Energy and
575 Buildings 193: 160-173.
576 Yao, R, Wang, L, Huang, X, Niu, Z, Liu, F, Wang, Q, (2017)Temporal trends of surface urban
577 heat islands and associated determinants in major Chinese cities. Science of the Total
578 Environment 609:742–754.
579 Zhang, Y, Sun, L (2019) Spatial-temporal impacts of urban land use land cover on land surface
580 temperature: Case studies of two Canadian urban areas. International Journal of Applied
581 Earth Observation and Geoinformation 75:171-181.
582 Zhao, D, Wu, S, (2014) Responses of vegetation distribution to climate change in China.
583 Theoretical and Applied Climatology 117: 15-28.
584 Zhao, J, Chen, S, Jiang, B, Ren, Y, Wang, H, Vause, J, Yu, H, (2013) Temporal trend of green
585 space coverage in China and its relationship with urbanization over the last two decades.
586 Science of the Total Environment 442: 455–465
587 Zhang, Z, Lin, B (2019) Energy Conservation and Emission Reduction of Chinese Cement
588 Industry: From a Perspective of Factor Substitutions. Emerging Markets Finance and
589 Trade 55:967-979.
590 Zhou, Z, Deng, Q, Yang, G, Lin, Y (2018) Quantitative Study of Using Piloti for Passive
591 Climate Adaptability in a Hot-Summer and Cold-Winter City in China. International Journal of
592 Environmental Research and Public Health 15.
593

Figure 1

Spatial distribution of 180 cities in China

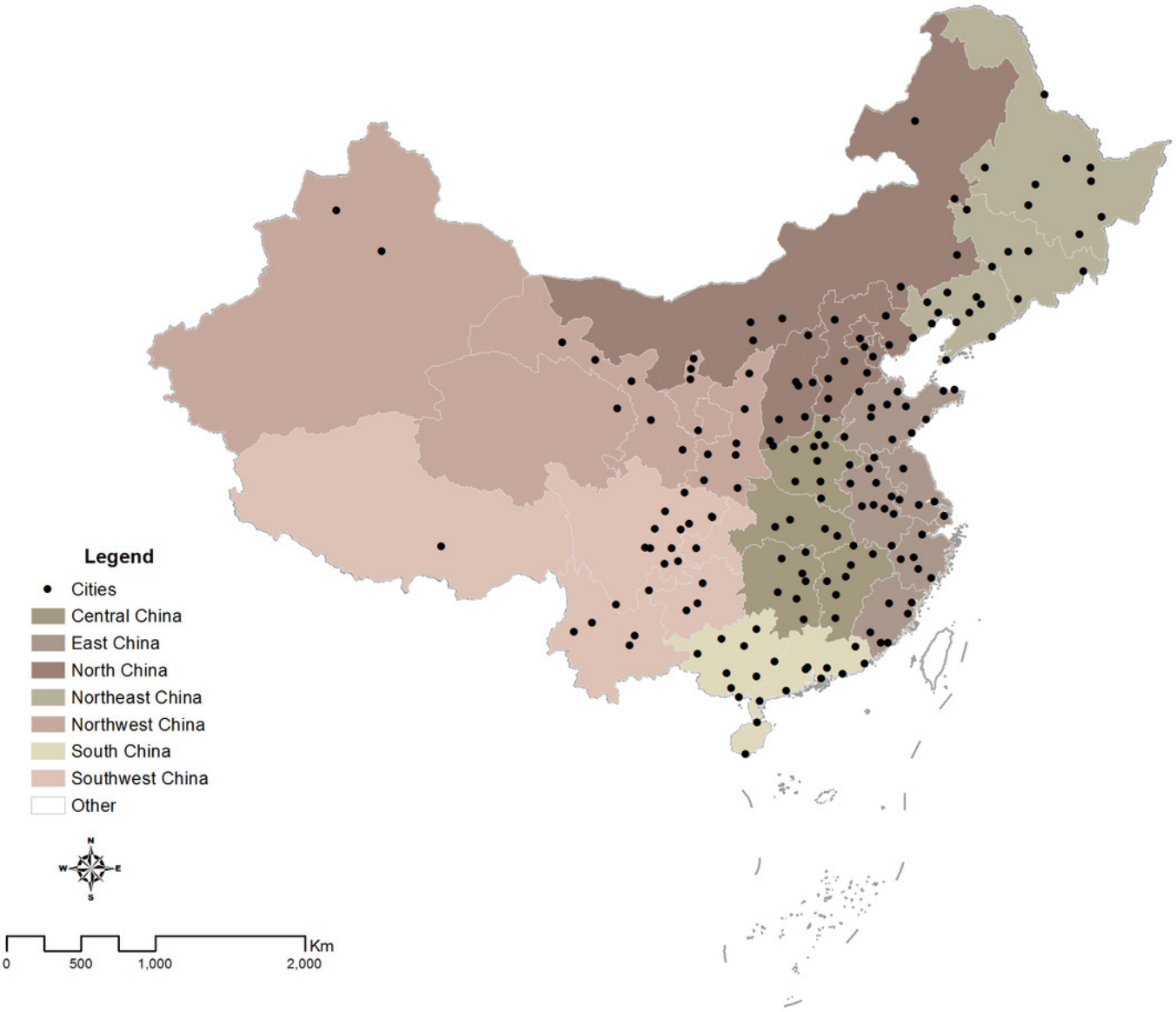
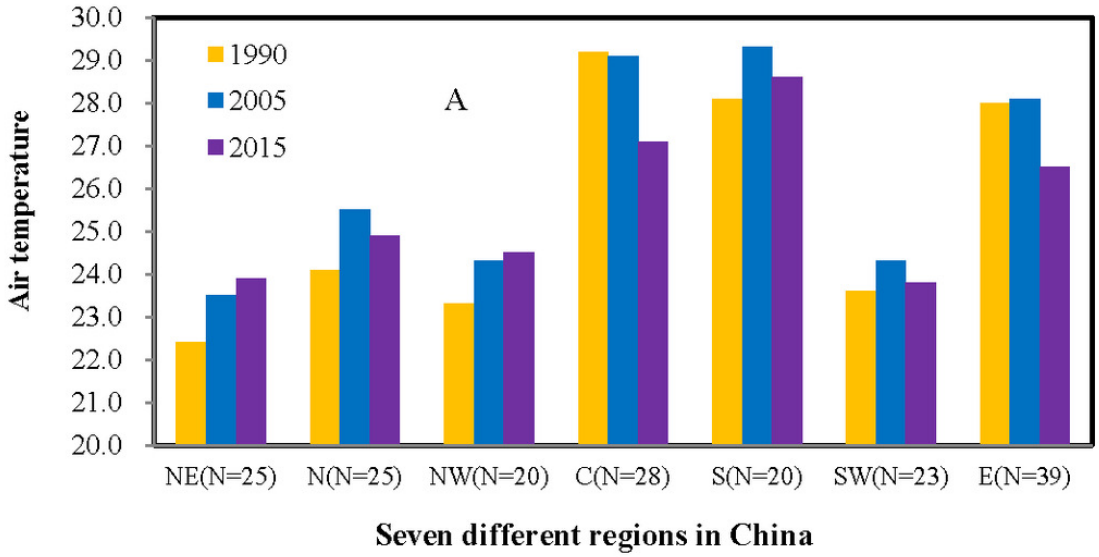
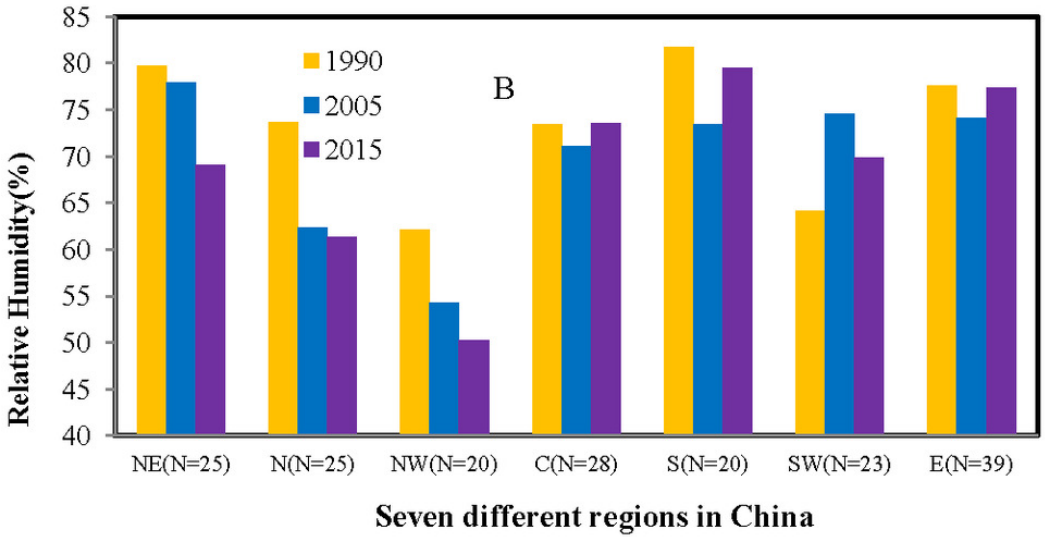


Figure 2

Changes of urban thermal parameters across different regions in China

Fig. 2. Changes of urban thermal parameters across different regions in China (NE:Northeast, N:North, NW:Northwest, C:Central, S:South, SW:Southwest and E:East)(A: Air temperature, B: Relative humidity,C:Wind speed).


30.0
29.0
28.0
27.0
26.0
25.0
24.0
23.0
22.0
21.0
20.0
Air temperature
1990
2005
2015
A
NE(N=25)
N(N=25)
NW(N=20)
C(N=28)
S(N=20)
SW(N=23)
E(N=39)
Seven different regions in China


85
80
75
70
65
60
55
50
45
40
Relative Humidity(%)
1990
2005
2015
B
NE(N=25)
N(N=25)
NW(N=20)
C(N=28)
S(N=20)
SW(N=23)
E(N=39)
Seven different regions in China

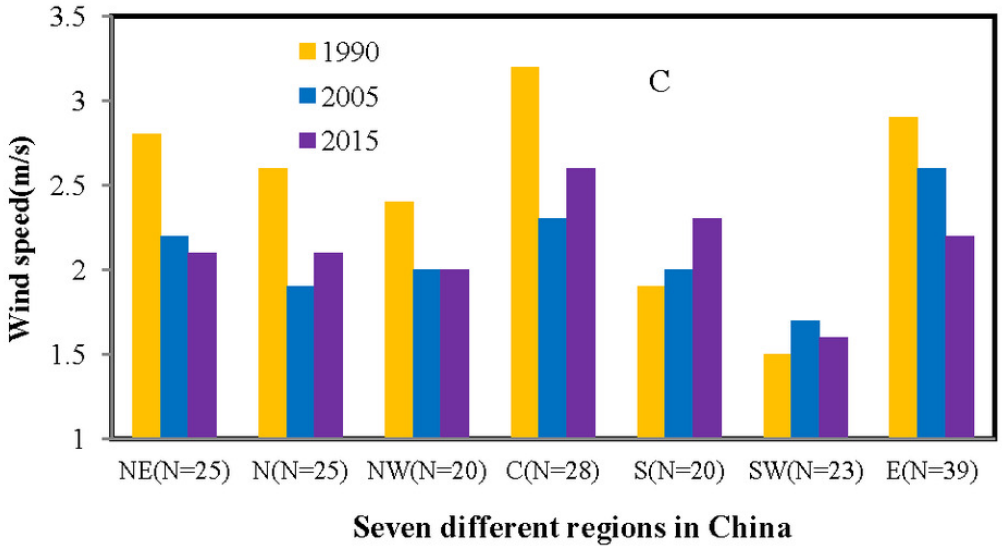

3.5
3
2.5
2
1.5
1
Wind speed(m/s)
1990
2005
2015
C
NE(N=25)
N(N=25)
NW(N=20)
C(N=28)
S(N=20)
SW(N=23)
E(N=39)
Seven different regions in China

Figure 3

Spatial pattern of PET across different regions in China

Fig. 3. Spatial pattern of PET across different regions in China (A: PET in 1990, B:PET in 2005,C: PET in 2015). <!--W]{��T-->

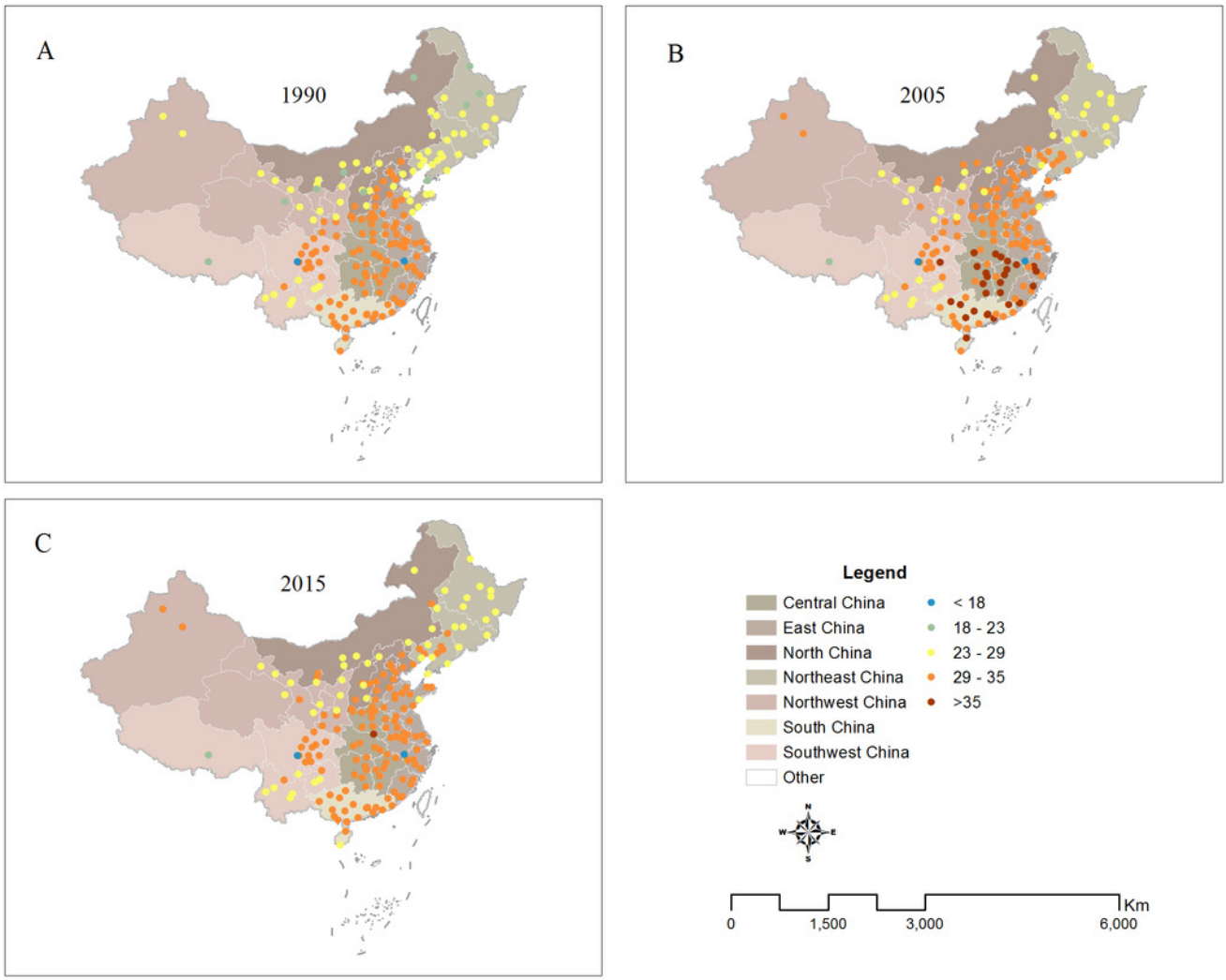


Figure 4

Histogram of the frequency statistics for PET

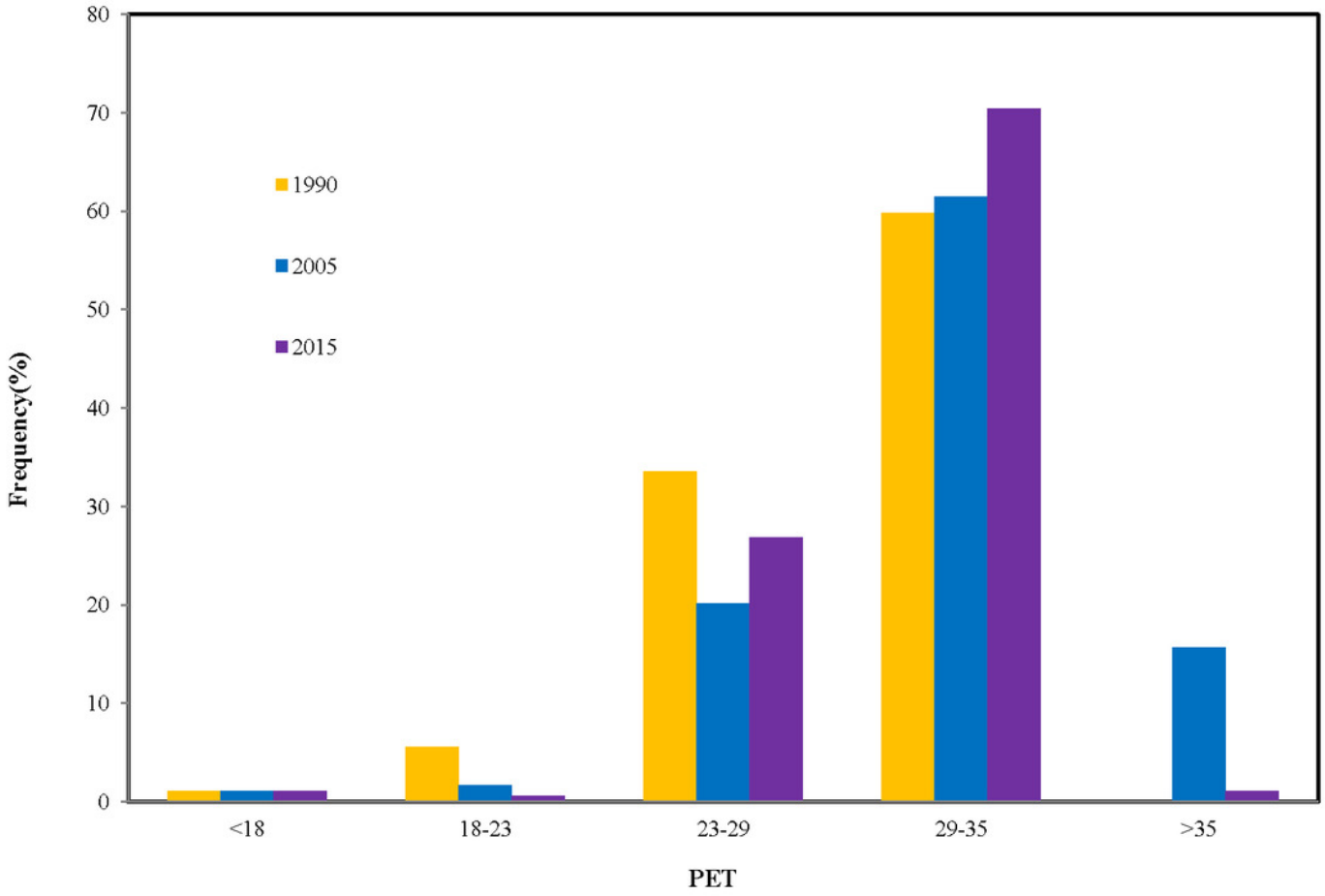


Figure 5

Spatial patterns of PET changes in different time periods and regions in China

Fig. 5 Spatial patterns of PET changes in different time periods and regions in China(A: PET from 1990 to 2005,B: PET from 2005 to 2015,C: PET from 1990 to 2015).

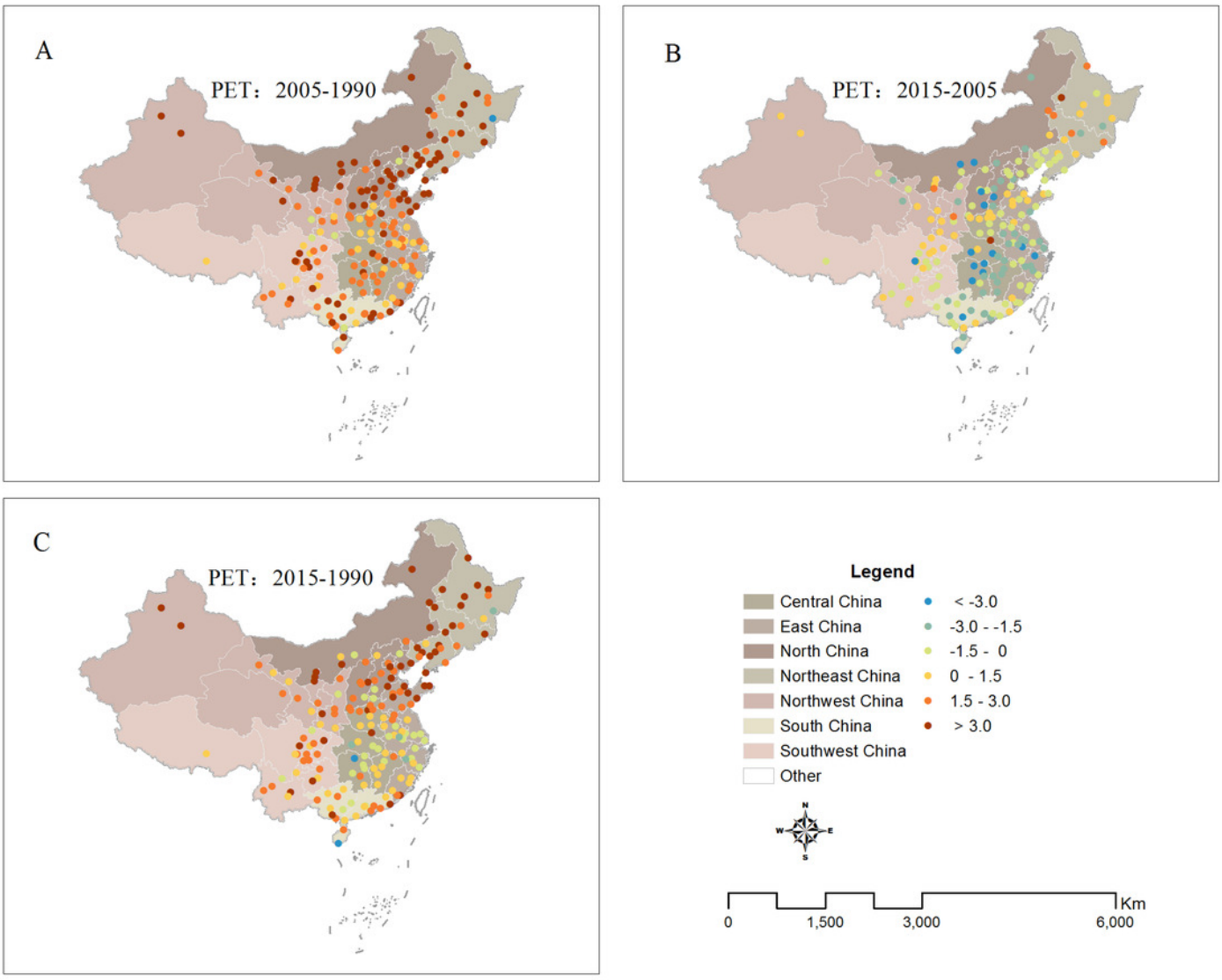


Figure 6

Histogram of the frequency statistics for PET changes across different years

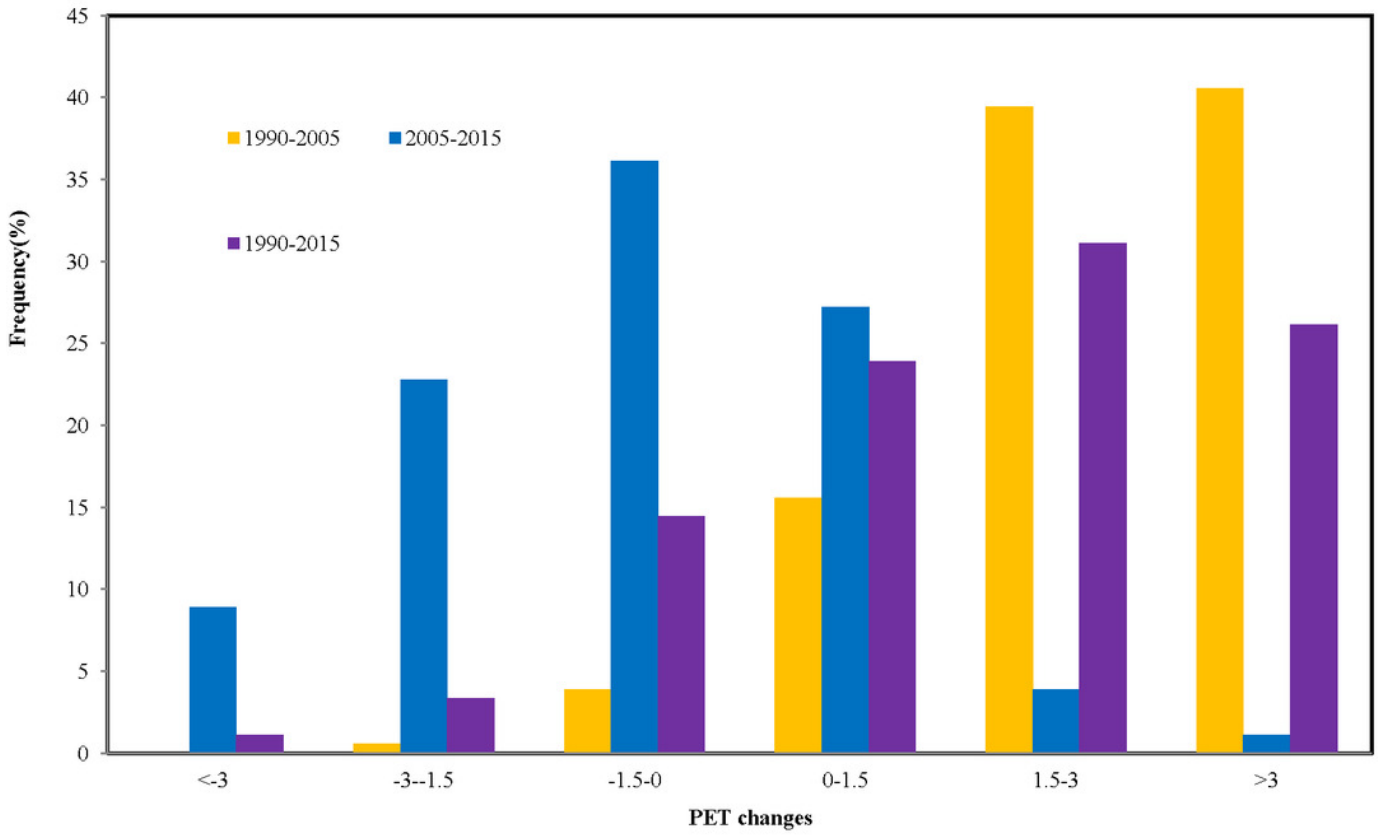
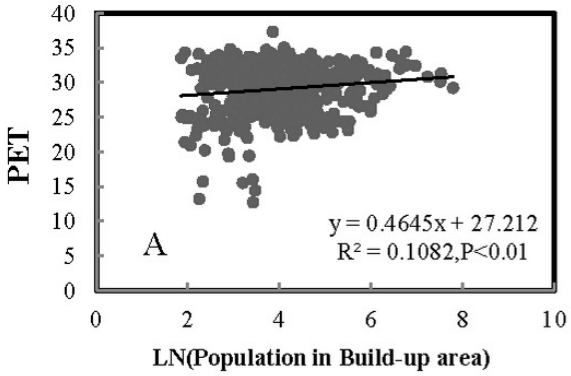
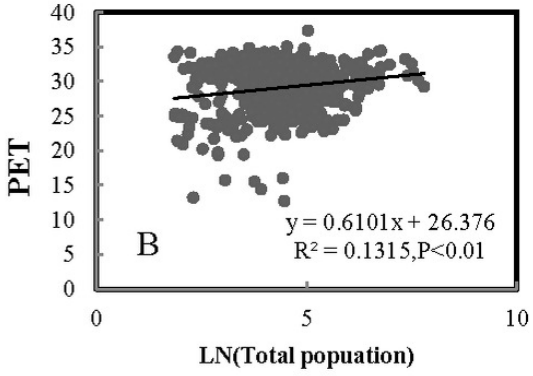


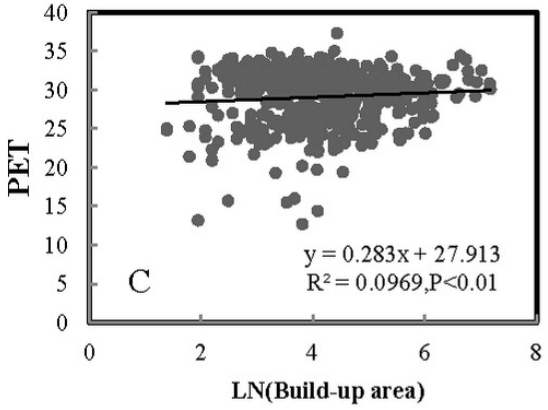
Figure 7

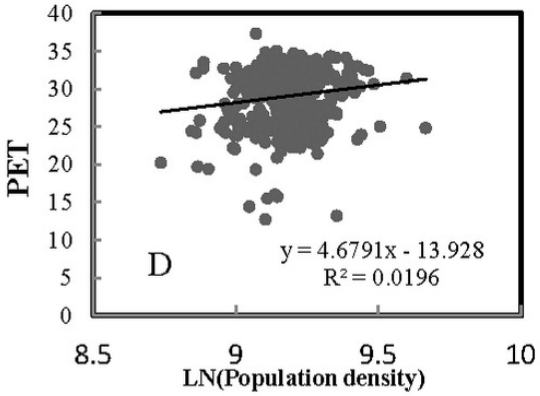
Regression analyses of urbanization with PET

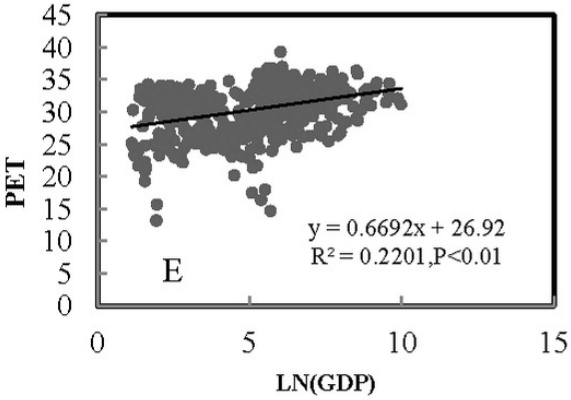
Fig. 7. Regression analyses of urbanization with PET (n = 540) (A:Population in Build-up area,B:Total population, C:Build-up area,D:Population density,E: GDP,F:Per capita GDP, G: Urban vegetaion coverage).

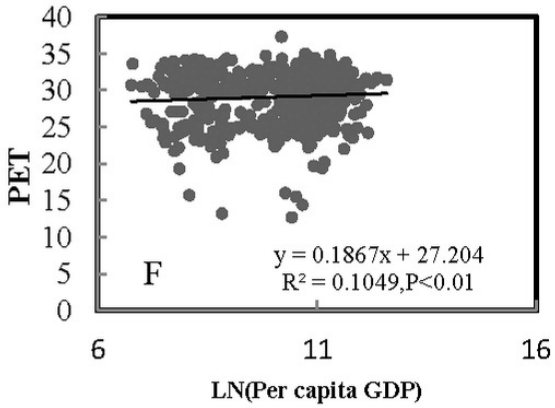

PET
A
y = 0.4645x + 27.212
R² = 0.1082,P<0.01
LN(Population in Build-up area)


PET
B
y = 0.6101x + 26.376
R² = 0.1315,P<0.01
LN(Total popuation)


PET
C
y = 0.283x + 27.913
R² = 0.0969,P<0.01
LN(Build-up area)


PET
D
y = 4.6791x - 13.928
R² = 0.0196
LN(Population density)


PET
E
y = 0.6692x + 26.92
R² = 0.2201,P<0.01
LN(GDP)


PET
F
y = 0.1867x + 27.204
R² = 0.1049,P<0.01
LN(Per capita GDP)

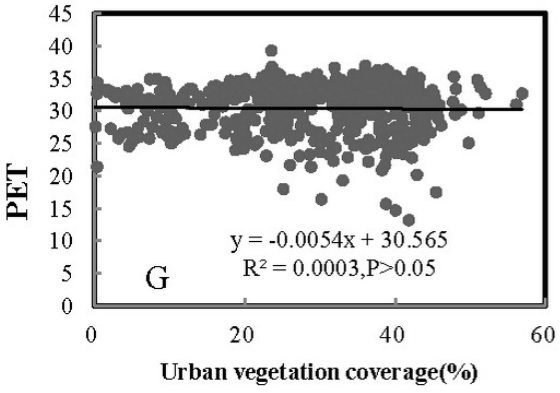

PET
G
y = -0.0054x + 30.565
R² = 0.0003,P>0.05
Urban vegetation coverage(%)

Table 1(on next page)

The average urban climte in 1990, 2005, 2015, 1990s, 2000s, and 2010s in China

The average urban climte in 1990, 2005, 2015, 1990s, 2000s, and 2010s in China

Table. 1. The average urban climte in 1990, 2005, 2015, 1990s, 2000s, and 2010s in China

Urban climate	1990	2005	2015	1990s	2000s	2010s
Temperature(℃)	25.3	26.8	26.1	24.9	27.1	25.8
Humidity(%)	75.8	70.4	68.3	75.13	71.3	67.7
Wind speed(m/s)	3.1	2.1	2.3	2.8	1.9	2
Solar radia(W/m^2)	393.4	389.5	401.2	390.5	386.7	398.5

Table 2(on next page)

Thermal sensation classes for human beings

Table. 2. Thermal sensation classes for human beings.

PET (◦C)	Thermal Perception	Grade of physical stress
> 42	Very hot	Extreme heat stress
35 – 42	Hot	Strong heat stress
29 – 35	Warm	Moderate heat stress
23 – 29	Slightly warm	Slight heat stress
18 – 23	Comfortable	No thermal stress
13-18	Slightly cool	Slight cold stress

Table 3(on next page)

The statistical description of urbanization and meteorological parameters in China

Table. 3. The statistical description of urbanization and meteorological parameters in China.

Urbanization and urban climate	1990	2005	2015
urban vegetation cover(%)	17.9a	32.2b	38.8c
Urban population(10^4)	58.4a	118.9b	136.6c
Built-up area（km^2）	45.4a	117.9b	160.2c
Population density(n/km^2)	12013.3c	9629.8b	7777.9a
GDP	38.3a	785.7b	1583.9c
Per capita GDP	5806.9a	53105.7b	68682.6c
Temperature(℃)	25.3a	26.8b	26.1b
Humidity(%)	75.8a	70.4b	68.3c
Wind speed(m/s)	3.1a	2.1b	2.3b
Solar radia(W/m^2)	393.4a	389.5a	401.2a

Values with different letters indicate statistically significant differences among the three different years at P-value < 0.05

Table 4(on next page)

Descriptive statistics of PET for 180 cities in China

Table. 4. Descriptive statistics of PET for 180 cities in China.

Year	1990	2005	2015
Min	13.2℃	17.5℃	14.7℃
Max	34.3℃	37℃	39.3℃
Average	28.7℃	31.7℃	30.6℃
SD	3.9℃	3.4℃	3.3℃

Table 5(on next page)

Pearson correlation coefficients between PET and urbanization

Table 5. Pearson correlation coefficients between PET and urbanization (n = 540).

Urbanizaiton indices	Pearson coefficients
Total urban population	0.136**
Urban population in build-up area	0.182**
Built-up area(km2)	0.164**
Population density(n/km2)	0.022
GDP(108 Yuan)	0.168**
Per capita GDP(Yuan/person)	0.234**
Urban vegetaion coverage (%).	-0.018

** Correlation is statistically significant at the 0.01 level (two-tailed).

Table 6(on next page)

Summary of the multiple regression models, in which PET is a response variable, and urbanization variables are predictors

Table 6. Summary of the multiple regression models, in which PET is a response variable, and urbanization variables are predictors

Variable	Lable	Cofficient	Std Coeffcient	t	p
Constant		25.759	0	32.667	<0.001
GDP	b1	1.265	0.655	8.443	<0.001
BA	b2	-2.039	-0.573	-6.072	<0.001
TP	b3	1.104	0.307	3.842	<0.001
VS	b4	0.051	0.167	3.822	<0.001

Notes: BA is "built-up area(km^2)"; TP is "total urban population"; andVC is "urban vegetaion coverage (%)".