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# Assessment of urban effect on observed warming trends during 1955–2012 over China: a case of 45 cities

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**Abstract** This study aims at qualifying the contribution of the urban effect to the total warming recorded by 45 urban or suburban stations in China where rapid and extensive urbanization over the last few decades occurred. Partly due to differences in urbanization and stations' geographic location, the total warming trends for 1955–2012 vary from of −0.10 to 0.49 °C and −0.03 to 0.64 °C per decade for the annual averaged daily mean and daily minimum temperature, respectively. A principal component analysis of seven factors on the siting and geographical coordinates of the meteorological stations shows three dominant factors (urban size, relative position of meteorological station to city center and geographic location of station) accounting for 87.1 % of the total explained variance. An index quantifying the impact of the first two dominating factors of the urban effect is proposed considering also the dominating wind direction. The positive correlation between the temperature trends and the index is significant ($P<0.05$), indicating that urbanization has significantly influenced the

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warming trends at these stations. The average contribution of the urbanization for all the stations to the total mean temperature trend is estimated to be 19 %.

**Abbreviations**

| | |
|---|---|
| Au | Urban area: Built-up land area, in $km^2$ |
| Dir | Direction: Direction of meteorological station relative to city center, 16 azimuth |
| Dis | Distance: the distance from meteorological station to city center, in km |
| NDVI | Normalized Difference Vegetation Index, unitless |
| OLS | Operational Linescan System |
| PC | Principal component |
| PCA | Principal Component Analysis |
| Pop | Population: non-agricultural population, in million |
| R | Radius: the radius of city shape simplified as circle, in km |
| Rd | Distance coefficient: the ratio of Dis and R, unitless |
| $T_{max}$ | Annual mean daily maximum temperature, in °C |
| $T_{mean}$ | Annual mean daily temperature, in °C |
| $T_{min}$ | Annual mean daily minimum temperature, in °C |
| UHI | Urban Heat Island |
| Uii | Urban impact indicator: the degree of the urbanization impact on the recorded surface temperature, in % |
| ESM | Electronic Supplemental Material |

## 1 Introduction

Human-induced climate change can be caused by both changed atmospheric composition and changed land-use, such as urbanization and agriculture (Kalnay and Cai 2003). During recent decades, the greenhouse effect has contributed most to the observed warming in surface temperature (Stocker et al. 2013). However, a portion of the total warming may be related to the UHI effects caused by urbanization (e.g., Griffiths et al. 2005). Because the UHI effect is considerable and many meteorological stations are located in or close to cities in China (Zhou et al. 2004), the recorded warming at these stations is often a result of the two factors, making it difficult to assess respective contributions to the warming for areas close to these stations.

Local-scale effects of urbanization on the climate have long been well documented (e.g., Upmanis and Chen 1999). The impact of urban area on local temperature is usually revealed by comparing the simultaneous temperatures above an urban surface and a non-urban surface (e.g., Heusinkveld et al. 2014). In one extreme case, a UHI effect as high as 10.7 °C was recorded in dense residential and commercial areas of Sitaram Bazar (Delhi) during night time (Mohan et al. 2013). Similarly, warming over larger regions caused by urbanization has been found in long-term average temperature datasets (e.g., Winkler et al. 1981). Yang et al. (2011) found that UHI effects contributed 24.2 % to the average warming trends during 1981–2007 over east China.

Although the studies mentioned above indicate that UHI significantly influences the local temperature change, most existing findings are limited to urban microclimate data (comparing urban stations with nearby rural stations in the temperature records). In addition, most studies did not consider the influence of wind which could carry the warmth to downwind areas. It is well known that downwind heat plumes (Clarke 1969) can extend over considerable distances, causing different temperatures in upwind and downwind areas of the city (Heusinkveld et al. 2014). Zhang et al. (2009) found that upwind urbanization exacerbates UHI effects and that meteorological consequences of extra-urban development can cascade well downwind. The impact of UHI on temperature is also related to the distance from meteorological station to city center. Knight et al. (2010) found an inverse relationship between temperature and distance from the city center in Manchester. Moreover, population size (Karl et al. 1988; Tran et al. 2006) and built-up area density (Heusinkveld et al. 2014) are related to the magnitude and extent of the UHI effect. Overall, the impact of urbanization on temperature recorded by meteorological stations not only relates to the size of urban area, but also to relative position of meteorological station to city and the directions of wind coming from the city.

The purpose of this study is to quantify the contribution of the wind direction-corrected UHI effect to the total warming recorded at urban or suburban meteorological stations in China. The result is important in comparison to regional scale climate change caused by the enhanced greenhouse effect. We will proceed in the following way: section 2 describes the study area, data and method used, while section 3 presents the results of the analysis. Finally, section 4 discusses the findings in order to come up with several conclusions in section 5.

## 2 Study area, data and methods

### 2.1 Study area

Because 98 % of China's territory is located between 20° and 50°N, temperate and subtropical climate types dominate and respectively account for 45 and 26 % of the total land area (Ding et al. 2013; Chen and Chen 2013). While the Siberian High affects almost the entire Asian continent in winter, a huge low pressure system located in northern India has a strong impact on the Asian summer monsoon and climate in China (Ding et al. 2013). Consequently, dry and cold northwest winds prevail during winter, while warm and humid southerly airflow dominates during summer.

### 2.2 Data

City data, including urban area (Au) and non-agricultural population (Pop), is from China City Yearbook 2007 issued by the National Bureau of Statistics of China (http://www.stats.gov.cn). Meteorological data including daily and annual mean climate data, were obtained from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/home.do). We chose the meteorological stations with long climate records (in the period 1955–2012). In addition, the annual maximum value of NDVI in 2009 which was calculated by the method of MVC (Maximum Value Compositing) was used to determine city area. The spatial and temporal resolutions of the SPOT-VEGETATION NDVI data are 1 km and 10 days, respectively. It was provided by the Environmental and Ecological Science Data Center for West China, National Natural Science Foundation of China (http://westdc.westgis.ac.cn).

## 2.3 Methods

### 2.3.1 Meteorological stations selection

Firstly, the top 200 cities close to the meteorological stations were selected based on Pop. There are 45 urban or suburban stations selected following three criteria: Au larger than 25 km$^2$, Dis less than 20 km, and a continuous climate data record covering the period 1955–2012 (Fig. 1; Table S1 and Table S2, ESM).

In addition, for determining the position of meteorological stations relative to the city center, city shape is assumed to be constituted by one or more circles with radius R (Eq. 1). If a city has a single center, Rd bigger than 1 means that the station is outside of the city, and Rd smaller than 1 means that the station is within the city (Eq. 2). If a city has two or three centers, Dis will be represented by the mean distance. R and Rd are calculated by the following formulae:

$$\mathrm{Au} = \pi \mathrm{R}^2 \tag{1}$$

$$\mathrm{Rd} = \frac{\mathrm{Dis}}{\mathrm{R}} \tag{2}$$

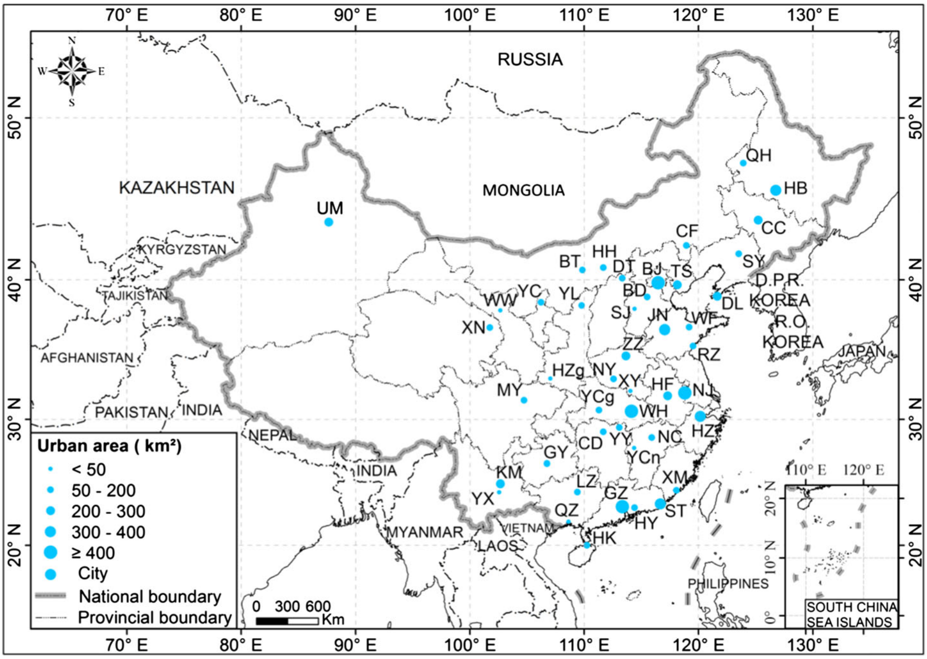

**Fig. 1** Locations of the 45 urban or suburban stations in China and their corresponding cities. City name (abbreviation) is as below: Baoding (BD), Baotou (BT), Beijing (BJ), Changchun (CC), Changde (CD), Chifeng (CF), Dalian (DL), Datong (DT), Guangzhou (GZ), Guiyang (GY), Haikou (HK), Hangzhou (HZ), Hanzhong (HZg), Harbin (HB), Hefei (HF), Hohhot (HH), Huiyang (HY), Jinan (JN), Kunming (KM), Liuzhou (LZ), Mianyang (MY), Nanchang (NC), Nanjing (NJ), Nanyang (NY), Qinzhou (QZ), Qiqihar (QH), Rizhao (RZ), Shantou (ST), Shenyang (SY), Shijiazhuang (SJ), Tangshan (TS), Urumchi (UM), Weifang (WF), Wuhan (WH), Wuwei (WW), Xiamen (XM), Xining (XN), Xinyang (XY), Yichang (YCg), Yichun (YCn), Yinchuan (YC), Yueyang (YY), Yulin (YL), Yuxi (YX), Zhengzhou (ZZ)

### *2.3.2 Urban area extraction and city center determination*

We first used conditional statements to filter the NDVI of urban areas (the detail of determining the NDVI range of urban areas can be found in Table S1, ESM). Then the raster data were converted to polygon vector data by using the Raster to Polygon Tool in ArcGIS10.0. Lastly, the polygons' geometric centers were calculated by the Feature to Point Tool, and taken to represent city centers. Because urban developments are not balanced, the urban geometry is complex and some cities have more than one geometric center (see Table S1 and S2, ESM). Figure 2 shows city areas and city centers of BJ (single-center) and YC (multi-centers) as examples.

### *2.3.3 Temperature change and urban impact*

**Trend detection** Using observed temperature data, the trends of $T_{mean}$, $T_{min}$ and $T_{max}$ of the 45 stations were calculated by linear regressions between annual mean temperature and year.

**PCA** PCA was used to extract the important information about urban effect from 7 factors including Au, R, Pop, Dis, Rd, as well as latitude and longitude of the meteorological stations (Abdi and Williams 2010).

**Indicator of urban impact** To quantify the impact of the first two PCs extracted by PCA and the influence of wind direction, an index (Uii) is proposed (equation is listed in Fig. 2). Uii is an indicator of the extent to which an urban meteorological station is influenced by winds traversing the built-up part of the city, and depends on the frequency distribution and the path length of winds of each wind directions across the city before reaching the meteorological station, summed over all wind directions. The path length used is the path length within the urban area ($L_1$) of each direction

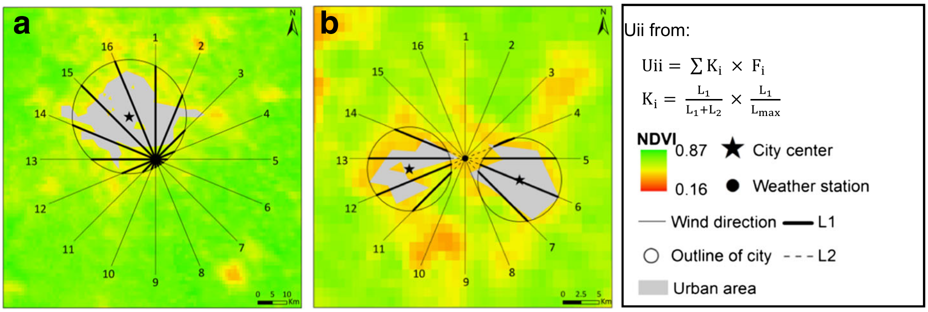

**Fig. 2** Sketches of city center, city area, wind direction for illustrative examples, **a** Beijing, **b** Yinchuan. (Wind directions are indicated using whole numbers from 1 to 16; Outline of city: simplified city shape with surface area equal to the built-up land area, and considering circle center as the city center; $L_1$: Impact length: impact of the urban area on meteorological station along one certain wind direction, in km; $L_2$: The distance from meteorological station to city boundary along one certain wind direction, in km. If the station is within the outline of city, $L_2$ is equal to zero; $L_{max}$: The maximum impact length among 45 stations, in km. Using this maximum impact length, which in the present study occurs in BJ, Uii is standardized; Ki: Coefficient of wind frequency (i=1, 2, …, 16); Fi: Wind frequency: mean value of 10 year (during 2000–2009) data (i=1, 2, …, 16), in %)

with a fading length ($L_2$) from the boundary of city to the station. $L_2$ equals to 0 when a station is in the city, or a station is out of the city but wind is from outside to city. The Uii is standardized by the longest path length of Beijing City ($L_{max}$) for regional analysis (Table 1).

**Table 1** Uiis and temperature trends as well as their descriptive statistics of the 45 meteorological stations during 1955–2012

| Name | Uii (%) | Trend (°C per decade) | | | Name | Uii (%) | Trend (°C per decade) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $T_{mean}$ | $T_{min}$ | $T_{max}$ | | | $T_{mean}$ | $T_{min}$ | $T_{max}$ |
| BD | 14.00 | 0.28 $^{**}$ | 0.47 $^{**}$ | 0.11 $^{**}$ | NY | 5.99 | 0.17 $^{**}$ | 0.36 $^{**}$ | 0.02 $^{-}$ |
| BT | 19.36 | 0.43 $^{**}$ | 0.56 $^{**}$ | 0.28 $^{**}$ | QZ | 7.63 | 0.20 $^{**}$ | 0.23 $^{**}$ | 0.14 $^{**}$ |
| BJ | 38.22 | 0.40 $^{**}$ | 0.53 $^{**}$ | 0.22 $^{**}$ | QH | 3.32 | 0.32 $^{**}$ | 0.44 $^{**}$ | 0.17 $^{*}$ |
| CC | 4.56 | 0.37 $^{**}$ | 0.52 $^{**}$ | 0.17 $^{**}$ | RZ | 6.45 | 0.26 $^{**}$ | 0.23 $^{**}$ | 0.31 $^{**}$ |
| CD | 10.33 | 0.23 $^{**}$ | 0.31 $^{**}$ | 0.17 $^{**}$ | ST | 10.78 | 0.29 $^{**}$ | 0.29 $^{**}$ | 0.32 $^{**}$ |
| CF | 12.32 | 0.25 $^{**}$ | 0.31 $^{**}$ | 0.21 $^{**}$ | SY | 6.12 | 0.17 $^{**}$ | 0.14 $^{*}$ | 0.14 $^{**}$ |
| DL | 6.82 | 0.29 $^{**}$ | 0.33 $^{**}$ | 0.25 $^{**}$ | SJ | 5.29 | 0.34 $^{**}$ | 0.55 $^{**}$ | 0.11 $^{*}$ |
| DT | 13.40 | 0.30 $^{**}$ | 0.30 $^{**}$ | 0.23 $^{**}$ | TS | 19.13 | 0.27 $^{**}$ | 0.32 $^{**}$ | 0.22 $^{**}$ |
| GZ | 23.36 | 0.18 $^{**}$ | 0.20 $^{**}$ | 0.16 $^{**}$ | UM | 24.86 | 0.28 $^{**}$ | 0.43 $^{**}$ | 0.14 $^{*}$ |
| GY | 12.45 | −0.10 $^{*}$ | −0.03 $^{-}$ | −0.16 $^{**}$ | WF | 2.64 | 0.15 $^{**}$ | 0.19 $^{**}$ | 0.10 $^{*}$ |
| HK | 2.30 | 0.19 $^{**}$ | 0.28 $^{**}$ | 0.09 $^{-}$ | WH | 5.37 | 0.28 $^{**}$ | 0.41 $^{**}$ | 0.17 $^{**}$ |
| HZ | 29.53 | 0.32 $^{**}$ | 0.34 $^{**}$ | 0.27 $^{**}$ | WW | 5.77 | 0.34 $^{**}$ | 0.37 $^{**}$ | 0.16 $^{**}$ |
| HZg | 8.74 | 0.19 $^{**}$ | 0.27 $^{**}$ | 0.11 $^{**}$ | XM | 2.35 | 0.04 $^{-}$ | 0.05 $^{-}$ | 0.12 $^{**}$ |
| HB | 21.35 | 0.42 $^{**}$ | 0.51 $^{**}$ | 0.23 $^{**}$ | XN | 1.24 | 0.09 $^{*}$ | 0.05 $^{-}$ | 0.24 $^{**}$ |
| HF | 6.22 | 0.22 $^{**}$ | 0.24 $^{**}$ | 0.18 $^{**}$ | XY | 2.42 | 0.18 $^{**}$ | 0.26 $^{**}$ | 0.05 $^{-}$ |
| HH | 18.69 | 0.49 $^{**}$ | 0.64 $^{**}$ | 0.30 $^{**}$ | YCg | 8.80 | 0.11 $^{**}$ | 0.18 $^{**}$ | 0.04 $^{-}$ |
| HY | 15.23 | 0.20 $^{**}$ | 0.32 $^{**}$ | 0.06 $^{-}$ | YCn | 1.32 | 0.14 $^{**}$ | 0.25 $^{**}$ | 0.02 $^{-}$ |
| JN | 8.44 | 0.13 $^{**}$ | 0.23 $^{**}$ | 0.06 $^{-}$ | YC | 5.00 | 0.39 $^{**}$ | 0.45 $^{**}$ | 0.27 $^{**}$ |
| KM | 5.68 | 0.34 $^{**}$ | 0.50 $^{**}$ | 0.24 $^{**}$ | YY | 4.10 | 0.19 $^{**}$ | 0.29 $^{**}$ | 0.05 $^{-}$ |
| LZ | 14.46 | 0.16 $^{**}$ | 0.27 $^{**}$ | 0.03 $^{-}$ | YL | 10.25 | 0.30 $^{**}$ | 0.39 $^{**}$ | 0.17 $^{**}$ |
| MY | 13.37 | 0.12 $^{**}$ | 0.24 $^{**}$ | 0.02 $^{-}$ | YX | 1.03 | 0.19 $^{**}$ | 0.26 $^{**}$ | 0.06 $^{-}$ |
| NC | 5.86 | 0.18 $^{**}$ | 0.24 $^{**}$ | 0.13 $^{**}$ | ZZ | 23.85 | 0.26 $^{**}$ | 0.37 $^{**}$ | 0.11 $^{*}$ |
| NJ | 36.23 | 0.25 $^{**}$ | 0.30 $^{**}$ | 0.14 $^{**}$ | – | – | – | – | – |
| Descriptive statistics | | | | | | Mean | Median | Minimum | Maximum |
| | | | | Uii | | 11.21 | 8.44 | 1.03 | 38.22 |
| | | | | Trend of $T_{mean}$ | | 0.24 | 0.25 | −0.1 | 0.49 |
| | | | | Trend of $T_{min}$ | | 0.32 | 0.30 | −0.03 | 0.64 |
| | | | | Trend of $T_{max}$ | | 0.15 | 0.14 | −0.16 | 0.32 |

*Uii* urban impact indicator, %; *Trend* temperature change trend, in °C per decade; Significance level: $^{-}$, $^{*}$ and $^{**}$ means not significant at the 5 % level, significant at the 5 % level and significant at the 1 % level, respectively; *CV* coefficient of variation

The abbreviation of cities are the same as in Fig. 1 and in Table 1

**Impact of city on temperature trend** Using linear regression (two-tailed confidence *t*-test), the relationship between temperature trend and Uii was analyzed using SPSS version 19.0.

## 3 Results

### 3.1 Temperature change

#### *3.1.1 Trends of annual mean temperatures*

Most stations (44 of 45 stations) show a warming trend during 1995–2012 except GY (Table 1). The increasing trends in $T_{mean}$ are significant ($P<0.01$) at 42 stations. Furthermore, 41 and 27 stations show significant increasing trends ($P<0.01$) for $T_{min}$ and $T_{max}$, respectively. Only GY shows a statistically significant decreasing trend in $T_{mean}$ ($P<0.05$) and $T_{max}$ ($P<0.01$). The ranges of trends of $T_{mean}$, $T_{min}$ and $T_{max}$ are 0.59, 0.67 and 0.48 °C per decade, respectively (Table 1).

#### *3.1.2 Spatial distributions of temperature trends*

Obvious warming occurred mainly in northern China, whereas the only cooling trend was in GY in southwestern China (Fig. S1, ESM). Furthermore, the positive correlation between trend and latitude for $T_{mean}$, $T_{min}$ and $T_{max}$ is significant at the 0.1, 1 and 5 % significance level, respectively (Table 2). This positive relationship is a well-known feature under global warming (e.g., Chen and Drake 1986). However, the

**Table 2** The results of Pearson correlation test

| | Au | R | Pop | Dis | Rd | Latitude | Longitude |
|---|---|---|---|---|---|---|---|
| Au | 1 | | | | | | |
| R | $0.96^{***}$ | 1 | | | | | |
| Pop | $0.91^{***}$ | $0.92^{***}$ | 1 | | | | |
| Dis | $0.59^{***}$ | $0.65^{***}$ | $0.68^{***}$ | 1 | | | |
| Rd | −0.05 | −0.03 | 0.06 | $0.69^{***}$ | 1 | | |
| Latitude | 0.12 | 0.18 | 0.09 | 0.14 | −0.01 | 1 | |
| Longitude | 0.25 | $0.32^{*}$ | $0.35^{*}$ | $0.36^{*}$ | 0.09 | 0.24 | 1 |
| Trend of $T_{mean}$ | $0.26^{\#}$ | $0.29^{\#}$ | 0.24 | 0.14 | −0.12 | $0.53^{***}$ | 0.15 |
| Trend of $T_{min}$ | 0.23 | $0.26^{\#}$ | 0.17 | 0.07 | −0.20 | $0.48^{**}$ | 0.05 |
| Trend of $T_{max}$ | 0.21 | $0.25^{\#}$ | $0.25^{\#}$ | $0.28^{\#}$ | 0.13 | $0.37^{*}$ | 0.20 |

The significance of each correlation coefficient was determined using a two-tail Student's *t*-test

*Au* urban area: Built-up land area, in $km^2$, *R* radius: the radius of city shape simplified as circle, in km, *Pop* population: non-agricultural population, in Million, *Dis* distance: The distance from meteorological station to city center, in km; *Rd* distance coefficient: the ratio of Dis and R

$^{\#}$, $^{*}$, $^{**}$ and $^{***}$ means the correlation is significant at the 10, 5, 1 and 0.1 % significance level, respectively trends show great differences at some adjacent stations in this study. For instance, KM and YX show an evident warming (0.34 °C per decade) and slight warming (0.19 °C per decade) in $T_{mean}$, respectively (Table 1). This difference may reflect local effects such as urbanization. Regional aerosol and cloud effects may also have contributed to some of the regional variations (Liu et al. 2004).

### 3.2 What are the key urban and geographic parameters?

Table 2 shows that positive correlation coefficients among Au, R, Pop, and Dis are higher than 0.59 ($P<0.001$); the correlation between Dis and Rd is also significant ($P<0.001$). Furthermore, there are certain linear correlations among Latitude, Longitude and other factors. Because the seven factors are inter-correlated, they can be described by fewer PCs which are extracted by PCA. By extracting PCs with an eigenvalue > 1, three factor groups are clearly distinguished (Fig. 3): Pop, Au and R highly load onto PC 1which explains 51.5 % of the total variance; Dis and Rd highly load onto PC 2 which explains 20.1 % of the total variance; while longitude and latitude highly load onto PC 3 which explains 15.5 % of the total variance. Together, PC 1, PC 2 and PC 3 account for 87.1 % of the total explained variance.

In the following, we will label PC 1 as urban size, PC 2 as relative position of meteorological station to city center, and PC 3 as geographic location of meteorological station. The effect of the first three factors on temperature change may be derived from the following facts: although the geographic location of stations shows a significant effect on temperature, big cities are expected to exhibit more intense UHI, influencing temperature measurements locally (Tran et al. 2006), especially at meteorological stations which are close to the center of the city (Knight et al. 2010).

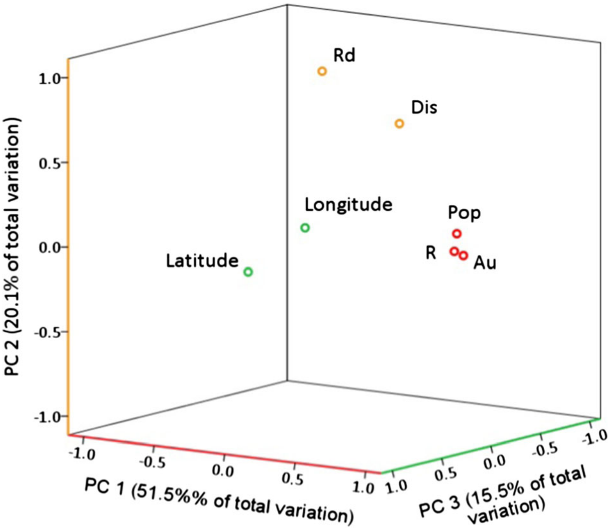

**Fig. 3** Illustration of seven factors ($n$=45) in the coordinate system of three principal components (PC) after orthogonal rotation. PC 1: urban size; PC 2: relative position of meteorological station to city; PC 3: geographic location of meteorological station; Latitude: latitude of meteorological station; Longitude: longitude of meteorological station. *Au* urban area, *R* city radius, *Pop* population, *Dis* the distance from meteorological station to city center, *Rd* the ratio of Dis. and R

### 3.3 Urban effect described by Uii

By design, Uii changes with time and space. We focus on spatial difference in Uii on temperature change trend in this study because they both are the generalized results over the time without considering the fine details of change processes (Kalnay and Cai 2003; Yang et al. 2011). We used estimates of Uii for all the 45 cities around 2007 to represent the spatial differences in urbanization effect in a relative sense. This approximation is due to the limited data availability, and is based on the assumption that the urbanization speeds over the study period across China are homogenous. We choose a later year during the study period as the urban effect most likely reached its maximum.

Table 1 shows the estimated Uii for the 45 meteorological stations. Fig. S2, ESM shows the space distribution of Uii of 45 stations in China. Obviously, there are 10 stations showing marginal impact from urbanization, and 7 of them are located in small cities (Pop less than 1.00 Million, see Table S1, ESM). Those stations showing slight impact are mainly concentrated in the central regions (30–40°N) of China; those showing medium impact are mainly located in the mid-north and mid-southwest; while those with strong impact are mainly located in northern and southeastern China (SI-2, ESM).

The distribution of the Uii indicates the difference of urbanization and economic development in China’s cities (Fig. S2, ESM). For instance, among the stations showing strong impact (Uii≥15 %), BJ and TS, NJ and HZ, GZ and HY stations are located in Circum-Bohai-Sea region, Yangtze River Delta and Pearl River Delta, respectively. All three regions are well developed regions in China in terms of economic growth.

### 3.4 Impact of city on temperature trend

Figure 4 shows the linear correlation between the trends for $T_{mean}$, $T_{min}$ and $T_{max}$ and Uii. The change rates of $T_{mean}$ and $T_{min}$ with Uii are 0.0041 °C per Uii in % and 0.0048 °C per Uii in %. These increases are significant ($P<0.05$), respectively. However, the correlation between the trend of $T_{max}$ and Uii is not statistically significant. Substituting the mean Uii (11 %) of the 45 stations into regression equations, the calculated result shows that the urban warming of $T_{mean}$ and $T_{min}$ are 0.046 and 0.054 °C per decade respectively. Because the total warming of $T_{mean}$ and $T_{min}$ are 0.24 and 0.32 °C per decade respectively (Table 1), the contributions of 45 cities urbanization to the total warming in $T_{mean}$ and $T_{min}$ are about 19 and 17 % respectively. The detail of calculation for contribution is shown in SI-4, ESM, the magnitudes of urban warming and their contributions to total warming for each station are shown in Table S3, ESM.

## 4 Discussion

In previous studies, urbanization bias has been estimated by studying the difference between reanalysis products and station observations (e.g., Zhou et al. 2004; Yang et al. 2011; Zhao et al. 2014), comparing homogenized station data sets with gridded temperature products (Jones et al. 2008), employing numerical modelling (Zhang et al. 2010), using satellite brightness temperature as a reference (Ren and Ren 2011), and comparing observed temperatures in urban stations with nearby rural stations (Zhou et al. 2004). Several studies focused on China have estimated different magnitudes of the UHI effect. While Li et al. (2010) found a contribution of the UHI effect to the total regional warming during 1954–2005 of less than

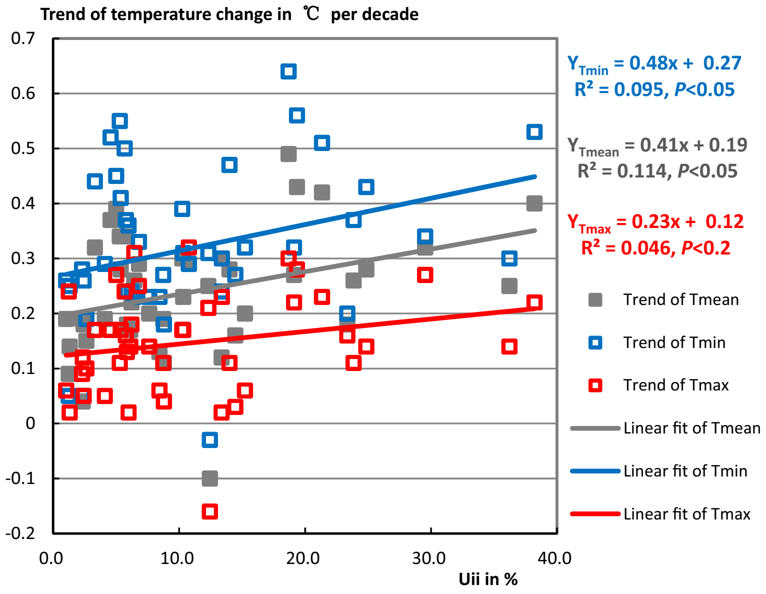

**Fig. 4** Temperature trends with Uii at the 45 meteorological stations. $R^2$ means the correlation coefficient which can show the significance level of correlation between Uii and temperature trend. $T_{mean}$, $T_{min}$, $T_{max}$ means annual mean daily temperature, annual mean daily minimum temperature and annual mean daily maximum temperature, respectively

10 % in northeast China, Ren et al. (2008) concluded that the contribution of urban warming to total annual mean surface air temperature change reached 37.9 % in North China. Another recent study (Wang and Ge 2012) came to the conclusion that the urbanization effect between 1980 and 2009 accounted for 20 % of the total warming over China. In studies for east China using reanalysis data, Yang et al. (2011) found that UHI effects contributed 24.2 % to the averaged regional warming trends, yet Zhao et al. (2014) showed that other variations such as the tropical Indian Ocean SST and the Siberian atmospheric circulation account for at least 80 % of the total warming trends. Like other countries, the differences in the estimates can be most likely attributed to different stations, regions and time periods used, but different methods employed also play a role (e.g., Kim and Kim 2011). Different approaches have their own limitations, which justifies the development of new and independent methods such as the one presented in this work.

Taking annual mean temperature as an example, the linear regression shown in Fig. 4 indicates that the urbanization is proportional to Uii and the contribution of urbanization can be as large as 0.15 °C per decade or 40 % of the total warming for BJ. Urban warming for large city in South Korea (Kim and Kim 2011) and densely inhabited areas in Japan (Fujibe 2011) were estimated to be about 0.2 °C per decade and 0.12 °C per decade respectively. Using satellite land use data, Wang and Ge (2012) classified Chinese meteorological stations into three groups, respectively displaying intense, moderate and minimal urbanization around the stations. They found that the contribution of urbanization to the total warming for the first two groups are 41 and 21 % respectively, i.e., greater than the estimate of the present study.

Compared with previous analyses (e.g., Hansen et al. 2001), the present study focuses on urban or suburban stations, which overcomes the difficulties linked to the data scarceness issue in rural areas. The composite index Uii takes into account the combined effect of several factors which are relevant for urban effect on temperature.

While our method uses spatially distributed samples with varying levels of urban influence and temperature trends to estimate the urbanization effect, other methods rely on direct comparison between an urban and rural site. The latter may suffer from two limitations. Firstly, the classified standards of urban/rural station are subjective and specific to the study area. Because thresholds in population data (Hua et al. 2008) or satellite night-light data (Owen 1998) to classify urban/rural station are site-dependent, previous results show great differences. For example, based on satellite night-light data, Peterson (2003) found no significant impact of UHI in the US with adjusted temperature data. On the contrary, based on both population data and the OLS night-light rankings, Stone (2007) reported that the warming differential between large US cities and rural sites during 1951–2000 was 0.05 °C per decade. Therefore, using suitable and current thresholds to classify the stations is a key issue in UHI research. Secondly, the number of selected urban and rural stations can be different. As we know, there is some difficulty in finding a pure "rural" station near each "urban" one (Li et al. 2004). Using a sample including a small number of rural stations may exaggerate the estimate of the UHI effect, but using a sample including many not purely rural stations may narrow this estimate (Ge et al. 2013). Also, reported estimates of the magnitude of urban-related trends or UHI effects are likely to be affected by the population sizes of the cities analyzed (Karl et al. 1988; Stone 2007).

The current study considers the position of the station in relation to city center as local advection can be important. Our index Uii includes this physical effect and the population information. Certainly, the method presented here also has its limitations. One such example is that we have to rely on the assumption that our sample size is big enough relative to the influences of other factors such as latitude and distance to the sea that may be considered white noise. Looking at Fig. 4, we feel that this assumption is pretty reasonable, except at the high end (big cities) of the data. Another future improvement lies in the possibility to estimate a temporally averaged Uii.

## 5 Conclusions

This study investigated the long term temperature trends recorded at the 45 urban or sub-urban stations in China in relation to urban effect. We have suggested a new urban impact indicator (Uii) to assess the magnitude of the urban impact on temperature trends. The following are the main results:

(1) Most stations experience warming during 1955–2012, the mean trends of $T_{mean}$, $T_{min}$ and $T_{max}$ are 0.24, 0.32 and 0.15 °C per decade respectively. However, the trends vary greatly in space.
(2) The temperature changes are significantly affected by geographic location of meteorological station, urban size, and relative position of meteorological station to city center.
(3) The mean warming caused by the urban effect in $T_{mean}$ and $T_{min}$ are estimated to be 0.046 and 0.054 °C per decade respectively, which implies that the contributions of the urban effect to the total warming in $T_{mean}$ and $T_{min}$ are about 19 and 17 % respectively.

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