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URBAN HEAT ISLAND EFFECT AND ITS CINTRIBUTION TO OBSERVED TEMPERATURE INCREASE AT WUHAN STATION, CENTRAL CHINA

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Abstract: Based on an in-homogeneity adjusted dataset of the monthly mean temperature, minimum and maximum temperature, this paper analyzes the temporal characteristics of Urban Heat Island (UHI) intensity at Wuhan Station, and its impact on the long-term trend of surface air temperature change recorded during 1961-2015 by using an urban-rural method. Results show that UHI effect is obvious near Wuhan Station in the past 55 years, especially for minimum temperature. The strongest UHI intensity occurs in summer and the weakest in winter. For the period 1961-2004, UHI intensity undergoes a significant increase near the urban station, with the increase especially large for the period 1988-2004, but a significant decrease is registered for the last 10 years, with the decrease in minimum temperature more significant than that of maximum temperature. The annual mean urban warming and its contribution to overall warming are 0.18°C/10yr and 48.8% respectively for the period 1961-2015, with a more significant and larger urbanization effect seen in T_{min} than T_{max}. A large proportion warming, about half of the overall increase in annual mean temperature, as observed at the urban station, thus can be attributed to the rapid urbanization in the past half a century.

Key words: Wuhan; Data in-homogeneity; UHII; Urban warming; Data bias; Climate change
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1 INTRODUCTION

Climate change research is mainly based on continuous and high-quality observational records. Due to the relocation of observation sites, replacement of observation instruments and changes in the time system, however, inhomogeneities have occurred in the observational data series to varying degrees, and they can cause a significant bias in analysis of surface climate variables trends for individual stations or a small area. Furthermore, the gradually increasing Urban Heat Island (UHI) effect near the observational sites becomes the biggest systematic bias for the long-term climate change monitoring and detection in that it directly causes the trend of Surface Air Temperature (SAT) records to be overestimated in many developing regions of the world.

At present, there exists a major divergence of views in the international climatological community on the impact degree of urbanization effect on the SAT series. It is generally hold that UHI effect is small, and it had not surpassed 0.05°C in the past a hundred years on a global average, much lower than the optimal estimation of the global average annual mean SAT change of 0.8°C (e.g., Jones et al.[1]; Peterson[2]; Parker[3]; Lawrimore et al.[4]). Nevertheless, some researches for several regions have shown that the UHI effect may play a significant role in the regional SAT trend, which should be paid more consideration (e.g., Karl et al.[5]; Hansen et al.[6]; Kalnay and Cai[7]; Zhou and Dickinson[8]; Zhou et al.[9]; Ren et al.[10]).

The studies of the UHI effect on SAT records have been conducted for big cities and large regions in recent years, and interesting conclusions have been drawn thereby. For example, the investigation of UHI effect in northern China for Beijing and Shijiazhuang stations has shown that the UHI Intensity (UHII) near the observational sites is stronger at night and in winter than during the day and in summer (e.g., Xie et al.[11]; Zheng et al.[12]; Ren et al.[13]; Yang et al.[14]); Deng et al.[15] pointed out that the UHII at night in Shanghai was the

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strongest in autumn/winter, while the UHII during the day was relatively stronger for the spring and plum rain season of early summer, and lowest in autumn. Meanwhile, studies also found that change trends of annual mean SAT observed at the meteorological stations were clearly influenced by the urban warming. For example, Huang et al.[16] showed that the annual mean SAT trend brought about by urbanization for southern coastal stations in China is higher than the background trend; Zhou et al.[9] found that the contribution of urban warming to the overall warming in the northern China region was 37.9% during 1961-2000, and it even reaches 71% at Beijing station over the same period (Chu et al.[17]); Urbanization-induced SAT trend reaches 0.19°C/10yr during 1962-2009 for Shijiazhuang station, accounting for 68% of all warming trend (Bian et al.[18]).

Wuhan, the capital city of Hubei Province, has a built-up area of approximately 400km^2 and a population of over 5millions with a rapid development and urbanization process. Wuhan city is located in the Jianghan Plain (Fig. 1), having severe heat wave and rainstorms in summer probably aggravated by urbanization effect during the past two decades. UHI effect is remarkable at Wuhan station since the 1980s, especially in winter, and the minimum temperature witnesses the highest contribution of urban warming to overall warming (e.g., Ren et al.[13]; Wu et al.[19]); Chen et al.[20] studied the UHI change trend for Wuhan station from 1960 to 2005, and found that the annual mean urban warming and contribution rate reached 0.235°C/10yr and 60.4% respectively. However, the previous researches only rely on the simple criteria to select reference stations, and the selected rural stations may have been gradually affected by UHI effect with the development of the small cities and towns themselves. There is a need to adopt a more objective method to select reference stations, and to assess whether or not the analysis results obtained by the new method are consistent with previous ones. In addition, it has been found that the temperature and sunshine hours in Wuhan decreased in recent 10 years (Cao et al.[21]), which is consistent with the global warming slowdown, and the relative humid (RH) experienced a rise in a certain degree after 2007 (Suonan et al.[22]). It is not clear whether UHI effect for Wuhan station will have some new features when the data are updated to present to include the period of climate warming slowdown.

In this paper, in-homogeneity adjustment is made for the SAT data updated to 2015. We analyze the climatological characteristics of UHI effect and the change of UHII with time near Wuhan station by using the homogeneous data from the urban station and two rural stations. Meanwhile, we estimate the urbanization effect on the long-term SAT change trend of the Wuhan station. The results of this paper are helpful for a further understanding of temporal characteristics of UHI effect, as well as nature and extent of urbanization-induced bias of SAT observation records for Wuhan station.

2 DATA AND METHODS

The monthly mean, minimum and maximum SAT data from 13 stations in Wuhan for the time period 1961-2015 and the MOD11A2 8-day LST product at 1-km spatial resolution in 0.02K unit from July 28 to August 4 in 2016 are used. The SAT are obtained from the National Meteorological Information Center of the China Meteorological Administration, which have already been quality controlled and the inhomogeneities caused by the artificial to automatic observation have been corrected. The SAT data at Caidian station missed in June, July and August in 1968 being replaced by monthly mean SAT data for 55 years.

Gallo et al.[23] used the vegetation index obtained from NOAA / AVHRR to explain the temperature difference between urban and rural areas. Ren and Ren[24] used MODIS data to select 113 SAT reference stations from 672 national reference climate stations and national basic meteorological stations of mainland China, pointing out that the method could be adopted for the adjustment study on the urbanization bias of the currently used air temperature records of surface climate stations. Compared to the other approaches used for classifying climatic stations, the remote sensing method does not rely so much on social and economic data. It is therefore feasible to use MODIS products to determine the regional boundaries of UHI-affected areas (Zhang[25]).

The remote sensing image quality is affected by the cloud cover. The Hubei area is controlled by the subtropical high in late July and the early August, and the weather condition is better. Therefore, the average LST from July 28 to August 4 in 2016 is used to determine the spatial distribution of ground surface temperature around the stations. The isothermal pattern of LST could reflect the temperature gradient from urban centers to suburbs less influenced by the UHI effect (Ren and Ren[24]). Winkler et al.[26] proposed that the boundary of the area affected by the UHI effect can be represented by the outermost closed isotherm of the annular temperature field in a city or town. In this paper, the outermost isotherm circle is 33.85°C and it can be taken as the boundary of the UHI-affected in the Wuhan city (Fig. 1).

The urban stations and the reference (rural) stations are determined according to the specific location of the station in the brightness temperature field. The stations which are located within the isotherm 33.85°C are regarded as the urban stations. The selection of the reference stations follows the following principles: (1) outside the closed contour 33.85°C of surface temperature; (2) the distance from the boundary of built-up areas within 30km to ensure in the same large-scale circulation and climate background with the urban stations; (3) elevation difference with the urban stations less than 20m, avoiding the influence brought by height difference; (4) the micro-environment around the rural stations is open.

The determination of rural stations is particularly important for studying the urban heat island effect. We therefore chose a more objective and strict method for the reference stations selection. Relative to other approaches to classify climatological stations, the remote sensing (RS)-based method is much less dependent on social and economic data, and RS data is also relatively continuous, with high spatial comparability and objectivity.

In addition to ensuring that all historical stations are outside the outermost contour when selecting a reference station, the distance to the city station, the altitude difference, and the environment around the sites are also taken into consideration. The distance and elevation difference are limited to ensure in the same climate background with urban station, as far as possible reducing the errors of results. In addition, many natural landscapes, such as lakes, basins and hills, also affect the surface thermal structure, and may result in the closed isotherms around the stations. These have also been taken into account when determining the reference stations.

The locations of all historical observation sites for Wuhan station are located within the 33.85°C (Fig. 1), and there has been a weak but a clear urban heat island effect at the urban station (Wang et al.[27]). We therefore consider Wuhan station as a representative urban station; the rural stations of all historical observation outside the closed circle of 33.85°C are Huangpi, Hanchuan and Anlu stations. The Anlu station is too far from Wuhan station and the elevation difference from the urban station is more than 20m (Table 1), so it is not taken as a reference station, and the relocation process of Anlu station is not shown in Fig. 1. From the Google earth images (Fig. 2), the locations of remaining rural stations are at the edge of the built-up areas, with little population and few buildings. It is clear that these two stations have not yet been significantly affected by nearby settlement and the UHI effect, and they can therefore be regarded as rural stations.

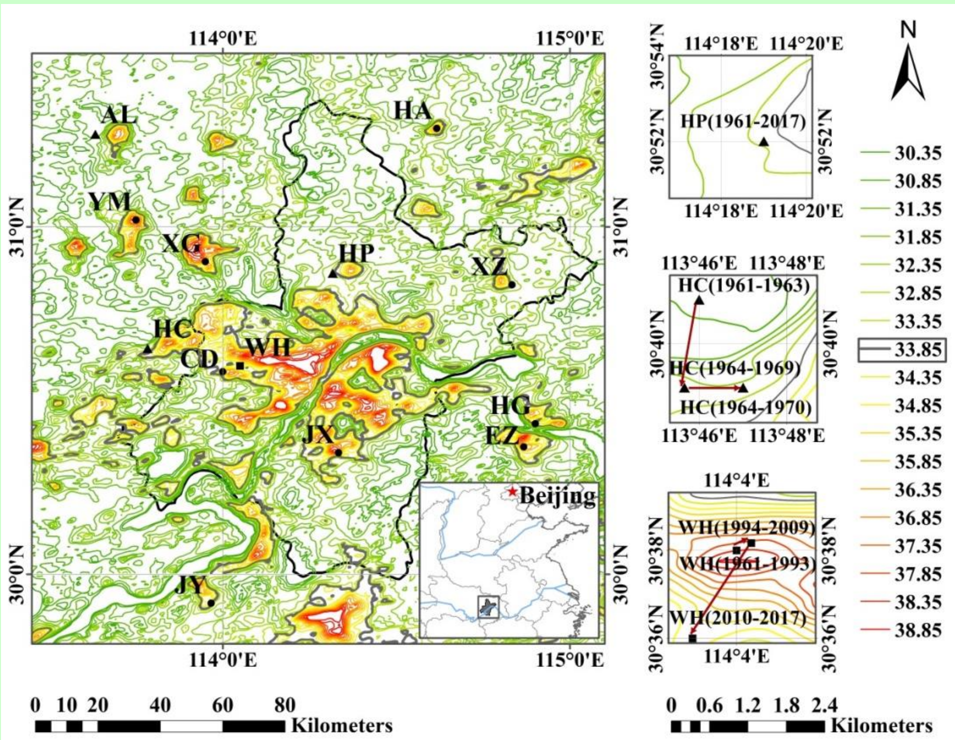

Fig. 1 The location of 13 stations and average LST isotherm distributions in Wuhan area. Abbreviations of the stations names are AL for AnLu, HA for HongAn, YM for YunMeng, XG for XiaoGan, HP for HuangPi, XZ for XinZhou, HC for HanChuan, WH for WuHan, CD for CaiDian, JX for JiangXia, HG for HuangGang, EZ for EZhou, and JY for JiaYu. The black line in the graph is the boundary of Wuhan city, and the relative position of Wuhan is shown in the illustration. The three enlarged figures on the right represent the relocation process of selected urban and rural stations, and the arrows show the relocation direction

Table 1. Information of the stations used in the study

Station name (Code)	Longitude (E)	Latitude (N)	Altitude (m.a.s.l.)	Distance from Wuhan station (m)	The time and distance of Relocations since 1961(km)
Wuhan (57494）	114.05	30.60	23.6	0	1994.4 (0.08); 2010.1 (8)
Hanchuan (57486)	113.78	30.65	27.0	26110	1964.1(6); 1970.11(3)
Huangpi (57491)	114.32	30.87	31.7	39100	
Anlu (57388)	113.63	31.27	55.5	84110	

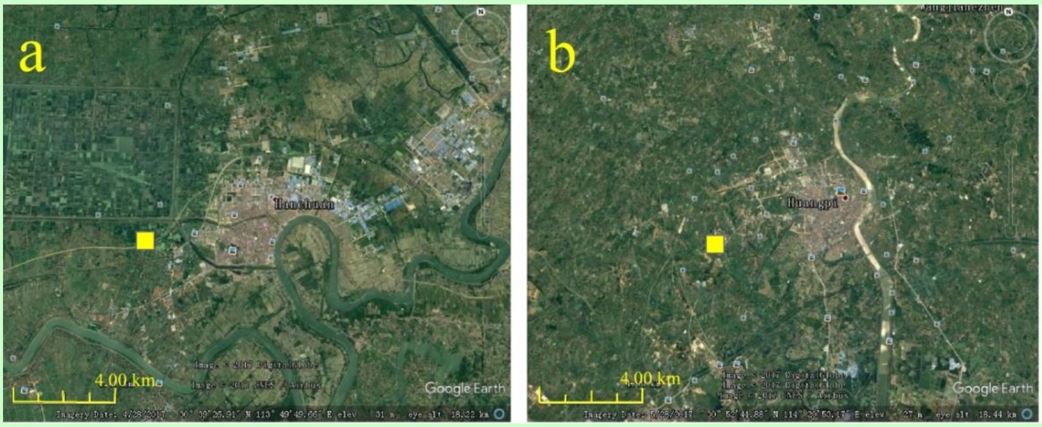

Fig. 2 Station and the surrounding landscapes as seen from Google Earth picture: (a) Hanchuan (No.57486), (b) Huangpi (No.57491)

The breakpoints of data series caused by relocations are examined for annual mean (T_{mean}), minimum (T_{min}) and maximum (T_{max}) SAT using E-P method (Easterling et al.[28, 29]). The autocorrelation problem needs to be considered in the in-homogeneity test. Annual mean SAT data series is less affected by the seasonal variability, reducing data series autocorrelation to a large extent (Cao et al.[30]). Therefore, in-homogeneity test and correction are based on the annual temperature data series in this paper.

Locations of the breakpoints could be determined based on whether or not the values of t statistics exceed the significance level. An adjustment could be made if the breakpoints could be proved to be real in reference to the metadata. The difference between the five-year average before and after the breakpoints is used as the adjustment value, and if the data is less than 5 years before and after the breakpoints, the longest time is taken to calculate the difference. Then annual adjustment values are interpolated linearly into the every month. Here, n=55, the length of the sub-series was 3 years, and the given significance level $\alpha = 0.05$.

After investigation of historical data, it is found that the relocation of Wuhan station in 2010 with a move of about 8 km has a significant impact on temperature series. The T_{mean} and T_{min} series both witnessed big breakpoints in 2010 by using moving t-test method. The breakpoints therefore for the T_{mean} and T_{min} data series are adjusted in the study. In order to ensure data uniformity, the T_{max} series also has been corrected despite the breakpoint in 2010 is undetectable. In the process of adjustment, we correct the SAT data after station moving by adding the adjustment values in order to better keep the UHI effect recorded at the original site (Wang[27])(Fig. 3).

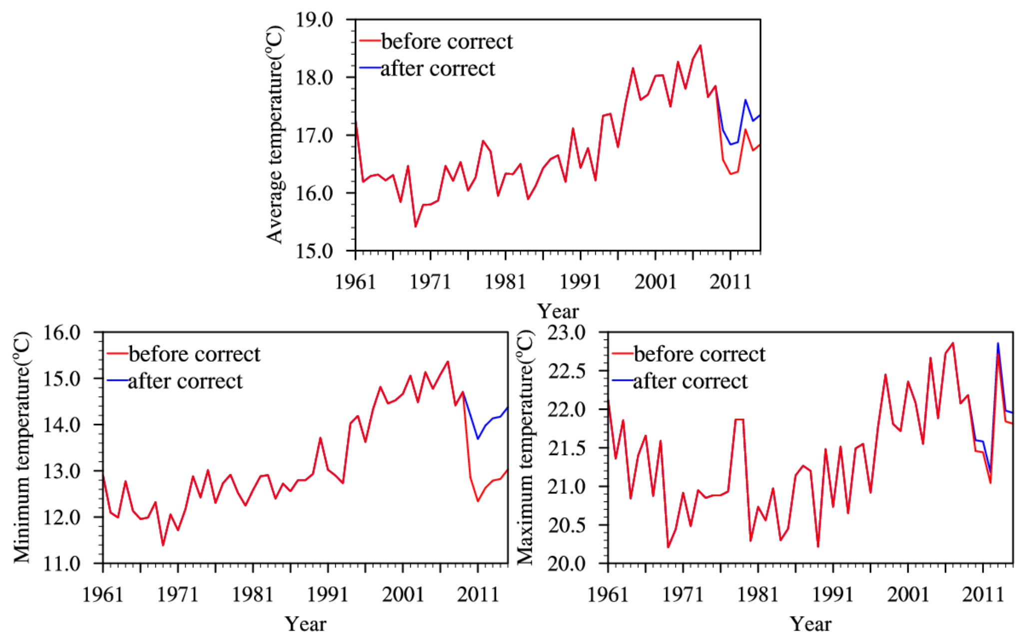

Fig. 3 Comparison of the series of annual mean, minimum and maximum temperature before and after homogenization at Wuhan station

Hanchuan station has moved for two times since 1961, but the data series has no detectable breakpoint probably because the relocation time was too early, and the data series has not been adjusted. Huangpi station has not been moved since its establishment, and this enables it to be an ideal reference station for examining the urbanization effect.

In the process of SAT data adjustment for Wuhan station, especially for the T_{mean} and the T_{min}, the corrected values are positive, indicating that T_{mean} and T_{min} originally drop sharply since 2010, which is largely due to the Wuhan station moving from the urban area to the suburbs at that time. There is a false cooling phenomenon in SAT series of Wuhan station caused by the relocation, and the warming trend of the corrected temperature series is more obvious than that of the original one (Fig. 3). The homogenization has regained the UHI effect and urban warming trend in the SAT series (Zhang et al.[31]).

UHII at Wuhan station is defined as the SAT difference between the urban and rural stations. The rural SAT or reference series is the average SAT of the two rural (reference) stations. Linear trends of the UHII series are obtained by using the least square method and the significance level of linear trend is examined by T test method. The difference of SAT linear trends between urban and rural stations is equal to the linear trend of the UHII series, and they are defined as urban warming or urbanization effect. Contribution of urbanization effect or urbanization contribution is the proportion of the statistically significant urbanization effect to the overall trend of SAT at the urban station (Ren et al.[10, 13]).

In practical calculations, the urbanization contribution may exceed 100%, probably brought by unknown local anthropogenic factors for rural stations in a few cases. In this case, it is adjusted to 100%. As indicated in the definition, if the urban warming is not statistically significant, the urbanization contribution will not be calculated and analyzed.

3 RESULTS AND DISCUSSION

3.1 *Climatological Characteristics of UHII*

Annual and seasonal mean UHII at Wuhan station for two periods of 1961-2015 and 1988-2015 are examined. As described later, UHII near Wuhan station is relatively weak before 1988, and a significant increase occurs afterward (Fig. 5).

The annual mean UHII at Wuhan station is 0.39°C for the period 1961-2015, the largest seasonal mean UHII is 0.47°C in summer, followed by 0.41°C in spring, 0.40°C in autumn, and 0.32°C in winter, but overall the seasonal difference is not significant (Table 2). The minimum temperature UHII is higher than the maximum temperature UHII, indicating that the UHII in Wuhan is stronger at night than the daytime. UHII has an obvious diurnal non-symmetry, which is consistent with most previous research results for the megacities of China (e.g., Zhou[32]; Xie et al.[11]; Zheng et al.[12]; Bian et al.[18]).

Table 2. Annual and seasonal mean, minimum and maximum temperature UHII for time periods 1961-2015 and 1988-2015 at Wuhan station (°C)

Period	Temperature	Spring	Summer	Autumn	Winter	Year
1961-2015	Mean	0.41	0.47	0.40	0.32	0.39
	Minimum	0.56	0.61	0.63	0.40	0.54
	Maximum	0.35	0.41	0.21	0.29	0.32
1988-2015	Mean	0.67	0.81	0.73	0.58	0.69
	Minimum	0.99	1.14	1.26	0.95	1.07
	Maximum	0.44	0.51	0.29	0.33	0.39

In the past 28 years, the seasonal feature of the mean UHII for Wuhan station is consistent with that of 1961-2015, the largest in summer and smallest in winter. The difference is that the three kinds of temperature UHII is larger during the recent period, with the minimum temperature UHII being the most obvious, almost two times the 1961-2015 period, followed by the mean temperature UHII, and the maximum temperature UHII change is the smallest. It shows that the UHII near Wuhan station has been enhanced since the late 1980s, which well corresponds to the rapid urbanization process in the city. The population and built-up areas in Wuhan had a rapid increase after the late 1980s and early 1990s, leading to an accelerating urbanization process (Xiao et al.[33]).

Whether the entire period or the recent 28 years, the seasonal mean temperature and maximum temperature UHII are the largest in summer, and the minimum temperature UHII is the strongest in fall. These features are different from the UHI effect of the metropolis in northern China in which the strongest UHII occurs in winter and the weakest in summer or spring (e.g., Bai et al.[34]; Zheng et al.[12]; Xie et al.[11]; Bian et al.[18]; Yang et al.[14]). This may be mainly due to the smaller solar elevation angle in winter (the zenith angle is larger), and the frequent temperature inversion and stable weather phenomenon controlled by the dry and cold Siberia air mass in winter in the north. Meanwhile, the humidity in lower atmosphere and cloudiness in northern China are usually less and anthropogenic heat release due to the heating is large in winter (Chen and Shi[35]). In contrast to winter, summertime in the north has a larger solar elevation angle (smaller zenith angle), and is more frequently affected by the southwest and southeast air currents, with more cloudiness and precipitation, and cooling energy consumption and artificial heat release in urban areas is smaller, leading to a generally lower UHI effect; the average wind speed in spring in the north is usually stronger, which is also against to the UHI formation and development.

Wuhan city belongs to the inland subtropical monsoon humid climate, with hundreds of lakes scattering in urban areas. In winter, the relative humidity and water vapor content of lower atmospheric are larger, and the anthropogenic heat release from urban heating is less, which may be the main reasons for the lower UHII in the cold season. In summer, the atmospheric humidity is high, with more cloudiness and precipitation, and the solar elevation angle is large (the zenith angle is small). These will not benefit the formation and development of UHI. However, the average wind speed in summer is weaker, and stable atmospheric layer and more sunny days prevail, because the city is controlled by the subtropical high in midsummer season (Wang[36]). Besides, the use of air conditioning in the summer is more common, with large anthropogenic heat release into the urban boundary layer. All of these will benefit the enhancement of the UHII in the urban areas during summertime. The weather in autumn is sunny with little cloud and the wind speed is small. In addition, the heat storage by abundant urban lakes makes boundary layer atmosphere warmer, enhancing the UHII. A higher seasonal mean UHII in autumn therefore results.

The seasonal variation feature of UHII at Wuhan station is similar to the other southern cities, such as Shanghai city and Guangzhou city, with larger UHII in autumn for mean and minimum temperature and significantly more obvious UHI phenomenon in spring and summer for maximum temperature. There is a big difference for the UHII of summer and winter for mean and minimum temperature between Wuhan station and other southern cities, however, and this may be related to the different underlying surface, geographical position and other factors (e.g., Xu et al.[37]; Deng et al.[15]; Zhou et al.[32]).

The seasonal variations of monthly mean UHII in the past 55 years and the past 28 years are similar (Fig. 4). The mean temperature UHII and minimum temperature UHII are the lowest in January, and then they gradually increase. The monthly mean temperature UHII reaches peak in July, and then slowly weakens, while the peak of minimum temperature UHII appears in September, and also higher in November for the recent 28 years. The monthly mean maximum temperature UHII has a different seasonal cycle, with the strongest in July and the weakest in October. It is thus obvious that the difference between the maximum and minimum temperature UHII in autumn is the largest in a year.

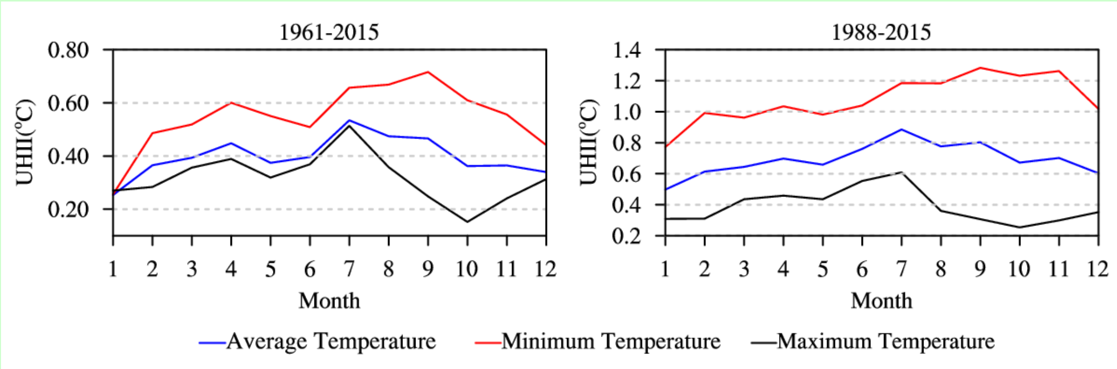

Fig. 4 Seasonal variation of monthly mean, minimum and maximum temperature UHII for time periods 1961-2015 and 1988-2015 at Wuhan station (°C)

The fact that maximum temperature UHII shows a downward trend after July can be explained by the increase in rainfall and cloudiness significantly accompanying the retreat of the subtropical high, with the suburbs and the city receiving similarly small amount of solar radiation during the daytime. The reduced anthropogenic heat release after mid-August might be another reason. In addition, large areas of lake and wetland in urban make night warmer and day cooler, with the latter offsetting the maximum temperature UHI effect to certain extent.

3.2 Urban Warming and its Contribution to Overall Warming

Fig. 5 provides the long-term change in annual mean, minimum and maximum temperature UHII at Wuhan station. Annual mean and minimum temperature UHII bears a consistent inter-annual and decadal variation, showing that UHII gradually increase since the early 1960s, especially for minimum temperature UHII as high as 33%, reaching peak around 2005 and dropping afterward. The maximum temperature UHII experiences a certain degree of decline in the 1960s, stable in the 1970s and 1980s, and a slow increase from the 1990s to 2004.

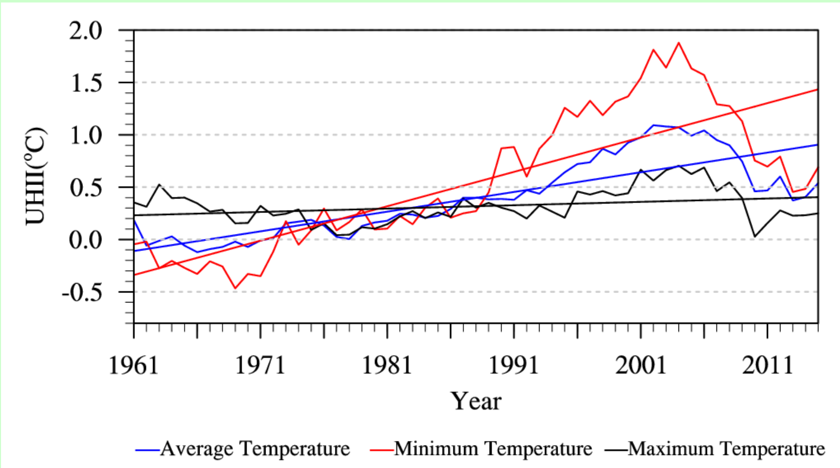

Fig. 5 Annual mean, minimum and maximum temperature UHII (polygonal lines) and their trends (straight lines) at Wuhan station

The UHII variations in the three kinds of temperatures are all characterized by lower values during the 1960s to the late 1980s, higher values after 1988. In general, the three kinds of temperatures UHII show an upward trend in the past 55 years, with an obvious rising in 1961-2004, the fastest increase (0.53°C/10yr for annual mean minimum temperature) in 1988-2004, and a decreasing in 2005-2015. Therefore, the long-term trends of UHII can be examined for four different time periods of 1961-2015, 1961-2004, 1988-2004 and 2005-2015.

Fig. 6 shows the urbanization-induced change in annual mean, minimum and maximum SAT, and the urbanization contribution to the overall warming at Wuhan station for the four periods. For the time period 1961-2015, the trend of annual mean UHII and the urbanization contribution are 0.18°C/10yr and 48.8%

respectively. A more evident urban warming and contribution occur in T_{min} than T_{max}. For the seasons, urban warming and contribution for T_{mean} are both highest in summer, followed by autumn. The largest urban warming of 0.37°C/10yr occurs in autumn T_{min}. Seasonal mean warming observed in summer T_{mean} can be entirely accounted for by the enhanced UHI effect.

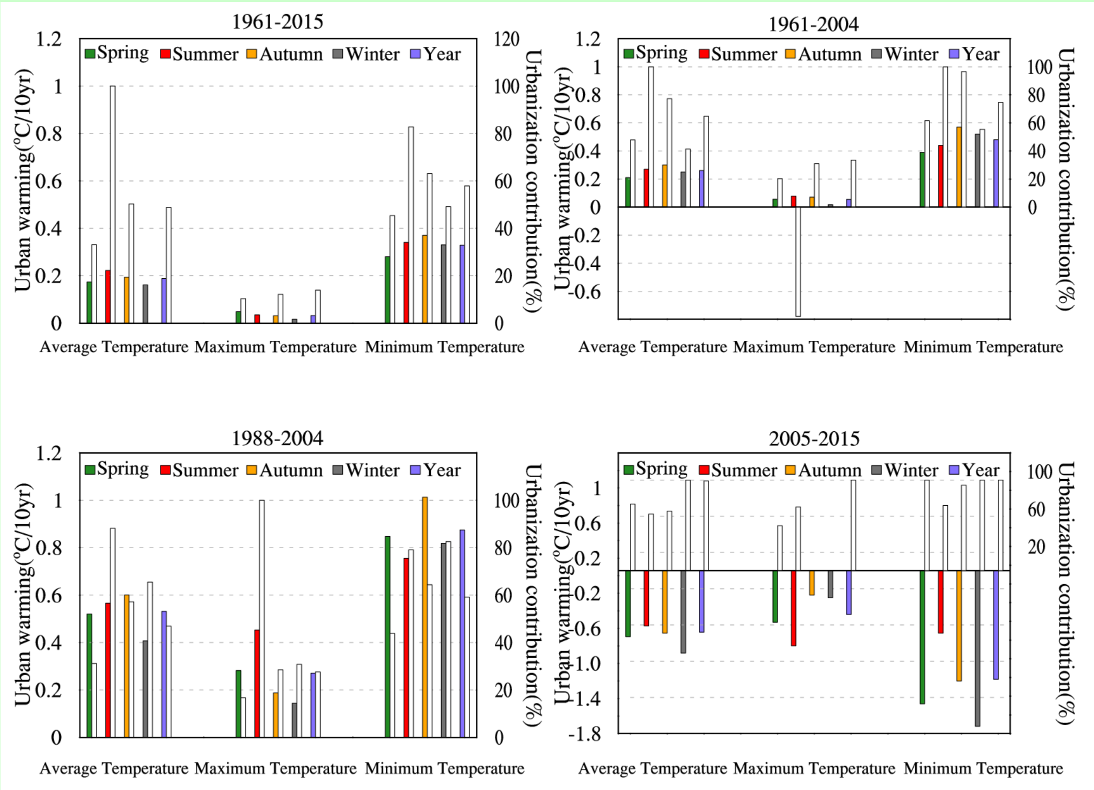

Fig 6. Urbanization effects (solid) and the urbanization contribution (blank) of seasonal and annual mean, minimum and maximum surface air temperature at Wuhan station

Seasonal mean urban warming and urbanization contribution for 1961-2004 are similar to those for the period 1961-2015, showing more evident change in summer and autumn. The difference is that contribution of urban warming in summer T_{max} is a negative value of -77.9%, implying that the background maximum SAT change during this period is characterized by a cooling trend and the urban warming is making an opposite contribution to the decrease at Wuhan station.

In comparison to periods 1961-2004 and 1961-2015, the urban warming during 1988-2004 is larger and more significant. Therefore, more significant urbanization effect at Wuhan station occurs during the late 20th century when urbanization and economic growth of China are unprecedented in history. The annual and seasonal mean, minimum and maximum temperature UHII trends are significantly greater than the other several stages, with more evident urban warming for summer and autumn T_{mean}. However, the urbanization contribution for summer T_{mean} becomes weaker relative to the periods 1961-2015 and 1961-2004. Autumn T_{min} witnesses the most significant urban warming reaching as high as 1.00°C/10yr, and the urbanization contribution as high as 65%, showing the warming observed at autumn night can be mostly accounted for by the urbanization effect.

Seasonal mean maximum temperature UHII trends and urbanization contribution during 1988-2004 are much larger than those in any other periods. This is especially true for summer, with the urbanization contribution even reaching 100%, indicating an entire contribution from the increased UHII to the positive trend of summer mean maximum temperature at the urban station (Fig. 6).

It is worth noting that the winter registers the relatively small urban warming but the quite significant urbanization contribution at Wuhan station, which is completely contrary to the results reported for the megacities of northern China (e.g., Chu and Ren[17]; Ren et al.[10]; Bian et al.[18]), where the UHII trends are the largest in winter, and the urbanization contribution to the overall seasonal warming is often smaller. This may be relative to the lower latitude, wetter and hotter climatic condition and larger proportion of wetland area in Wuhan city compared to the northern megacities. The anthropogenic heat-release difference of winter heating and summer cooling between northern and southern cities, and the different background circulation fields and multi-decadal climate variability, would be also important to the contrary seasonality of the urbanization effects.

It is worth noting that the rural stations unaffected by urbanization effect can hardly be found in central China. The rural stations used in this paper are currently available stations that are less affected by urbanization. Therefore, there is a certain degree of urbanization impact in the rural station temperature series. As a result, urban warming and their contributions to the overall warming in different time periods as given in this work for Wuhan station could be regarded as the lowest estimates.

China has witnessed a rapid urbanization process in the past half century, especially the past 30 years. From 1978 to 2015, the urbanization rate of the country increases from 17.9% to 50.0%. This phase is also accompanied by the obvious increase in urban heat island effect around the climatic stations (Ren et al.[10]). Through calculation, the urban land and construction land increase by 58% from 1988 to 2004 in Wuhan area, with the most significant urban warming of Wuhan station as high as 0.53°C /10yr, indicating that the rapid expansion of the city is the main reason for the increase of UHI effect recorded in the SAT series.

The above three time periods (1961-2015, 1961-2004 and 1988-2004) all undergo a significantly higher urban warming for T_{min} than T_{mean} and T_{max} at Wuhan station. This indicates that the UHI effect is more obvious at night than the daytime, which is mainly due to the greater thermal admittance in the urban area than that of the suburbs, leading to a slower temperature drop in urban after sunset. The urban buildings, with many urban street canyon, generally absorb more solar radiation than the suburbs during the daytime. There are downward long-wave radiations of walls and eaves in addition to atmospheric counter-radiation, coupled with the relatively low wind speed, and the heat is not easily dissipated at night in the urban area. All of these make the nighttime UHI effect higher than daytime, and the UHI effect at night will become more obvious with the development of the city, resulting a more rapid increase in T_{min} than T_{mean} and T_{max}.

During the period from 2005 to 2015, the annual and seasonal mean, minimum and maximum temperature UHII trends are negative, indicating that the UHII for Wuhan station is weakening in the past 10 years. The descending rates of urban warming for annual and seasonal mean T_{min} are much higher than the T_{max} except for the summer. Although the UHII is weakening in the last 10 years, the urban contribution is positive and still large. This may be related to the fact that the background SAT is experiencing a decrease during the period of climate warming slowdown, and the urban station undergoes a more rapid decrease than the rural stations do (Fig. 7). The relatively slower decrease in SAT at the rural stations may be caused by the increase of built-up areas around the observational sites in recent 10 years. The rural stations may therefore have been affected by urbanization. It is highly possible that the rural stations have become unrepresentative after 2005 due to the urbanization effect in these originally suburban areas.

The annual mean T_{mean}, T_{min} and T_{max} in urban and rural stations have decreased since 2005 (Fig. 7), which is consistent with the trend of temperature changes in China. Wang[38] pointed out that the annual mean temperature shows a certain degree of downward trend from 2005-2012. The warming hiatus since about 2000 is especially obvious in North China. The temperature decrease in recent decade in both urban and rural stations may therefore be caused by large scale drivers. The fact that the temperature decrease is more significant at Wuhan station than that at the rural stations makes annual mean, minimum and maximum temperature UHII to weaken during the nearly 10 years. The reasons for the more rapid decline of temperature at the urban station need to be further studied, but it is possible that the areas around the reference or suburban stations experience a more rapid urbanization than those around the urban station.

It is notable that the relative humidity(RH) has a certain recovery recently, and the RH series is inversely related to annual mean temperature series at Wuhan station, with the correlation coefficient reaching -0.65 for 1961-2015, and the urban heat island phenomenon is always accompanied by the urban dry island (e.g., Suonan et al.[22]; Zhou et al.[39]). Rising of RH in the last 10 years therefore is not conducive to the formation and development of urban heat island around the urban station. Besides, sunshine hours have declined after 2007 in Wuhan (Suonan et al.[22]), and the winter mean wind speed near the ground surface has strengthened in the period of climate warming slowdown (Lin et al.[40]). These, in combination with the background climate cooling of eastern China and the urbanization process around the rural stations, may also account for part of the greatly weakened UHII and the large downward trend of temperature during the last decade at the urban station.

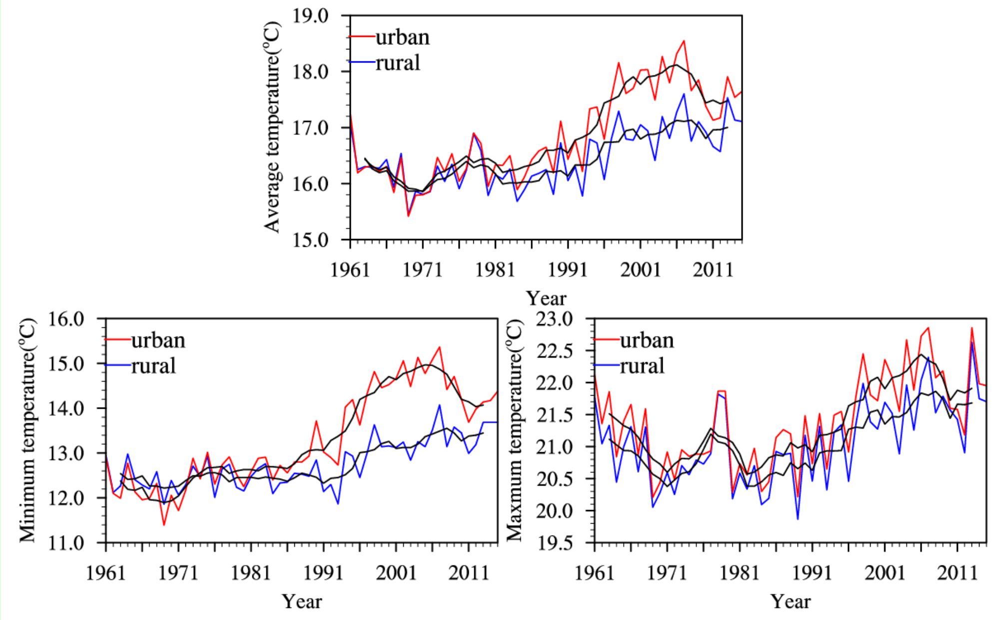

Fig. 7 Annual mean, minimum and maximum surface air temperature at Wuhan station and the two rural stations (average of two rural stations). Black solid line denotes 3 points moving average

The inhomogeneity in the observed SAT series has a significant effect on the long-term trend analysis. In this paper, the breakpoints due to the station moving are detected for the urban and rural stations. There is a sudden drop in temperature after Wuhan station moved to the suburbs in 2010, with the T_{min} difference is 1.35°C before and after the move. Historical data confirm that this decrease is not a true natural change, but an inhomogeneity error caused by the relocation (Liu et al.[41]). It makes the T_{mean} trend to drop from the 0.57°C/10yr to 0.43°C/10yr. Meanwhile, the three kinds of temperatures UHII will be weaker after 2010, especially the mean and minimum temperature UHII, if the inhomogeneity is not corrected. The effect of inhomogeneity caused by relocation on SAT series is obvious, and it is necessary to make reasonable adjustments.

Compared with previous studies on Wuhan station, we test and correct the inhomogeneities of SAT data, and use the more objective method of selecting the rural stations. The SAT data series is also updated. The conclusions are very similar to those previous works. The annual mean urbanization effect and contribution are 0.26°C/10yr and 64.7% respectively in this analysis, similar to those estimated in Ren et al.[13] (0.20°C/10yr and 64.5% for period 1961-2000), and Chen et al.[20] (0.24°C/10yr and 60.4% for period 1960-2005). The previous studies also showed that the urban warming is the highest in autumn and the second in summer, whereas the summer witnessed the largest urbanization contribution, followed by the autumn (Ren et al.[13]), which is basically the same with the results of this paper. In addition, Wang et al.[27] showed an annual mean urban warming of 0.31°C/10yr for Wuhan station for the period 1961-2010, larger than the value of 0.19°C/10yr for 1961-2015 in this paper. This difference may be mainly related to the updated data in this article, and the different rural stations applied in the two analyses.

The annual and seasonal mean urbanization effects have weakened when the data are updated to 2015, and also their seasonal distribution has a slight change with the largest urbanization effect now occurring in summer and the second largest in autumn. This may be related to the increase in anthropogenic heat release due to the recent wider use of air conditioning and refrigeration equipment in summer (Zhou[42]), as well as the compressed regulation effect of wetlands due to the rapid shrink of urban lake areas (Dan et al.[43]).

4 CONCLUSIONS

The annual mean UHII is 0.39°C for 1961-2015 at Wuhan station, and the UHI effect is more obvious during the recent 28 years, with the annual mean UHII and minimum temperature UHII reaching 0.69°C and 1.07°C respectively. The strongest monthly mean UHII appears in July, and the weakest in January.

The annual mean, minimum and maximum temperature UHII shows significant upward trends for the period 1961-2015. The annual mean urban warming and urbanization contribution are 0.18°C/10yr and 48.8% respectively, and larger and more significant urban warming and urbanization contribution are registered for T_{min}. The largest seasonal mean urban warming and urbanization contribution occur in summer.

The annual mean urban warming becomes more obvious with time, with urbanization effect reaching as high as 0.53°C/10yr for the period 1988-2004.The seasonal mean urbanization effect and urbanization contribution for the period 1988-2004 are both high in summer and autumn, with the greatest urban warming of higher than 1.00°C/10yr seen for autumn mean T_{min}.

From 2005 to 2015, the annual mean UHII for T_{mean}, T_{min} and T_{max} show evident decreasing trends. This decrease may have at least partially caused by the unrepresentativeness of the rural stations during the recent decade.

Therefore, the SAT data in Wuhan station has been significantly affected by urbanization. As an urban meteorological station, the long-term observational data of surface air temperature can be used to monitor and study urban climatology and urban climate change, but they are improper to be used in monitoring and studies of regional and global climate change without adjustment of the urbanization-induced bias, no matter if the homogenization of the data is made.

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