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RESEARCH ARTICLE

The relationships between urban-rural temperature difference and vegetation in eight cities of the Great Plains

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Abstract Interpreting the relationship between urban heat island (UHI) and urban vegetation is a basis for understanding the impacts of underlying surfaces on UHI. The calculation of UHI intensity (UHII) requires observations from paired stations in both urban and rural areas. Due to the limited number of paired meteorological stations, many studies have used remotely sensed land surface temperature, but these time-series land surface temperature data are often heavily affected by cloud cover and other factors. These factors, together with the algorithm for inversion of land surface temperature, lead to accuracy problems in detecting the UHII, especially in cities with weak UHII. Based on meteorological observations from the Oklahoma Mesonet, a world-class network, we quantified the UHII and trends in eight cities of the Great Plains, USA, where data from at least one pair of urban and rural meteorological stations were available. We examined the changes and variability in urban temperature, UHII, vegetation condition (as measured by enhanced vegetation index, EVI), and evapotranspiration (ET). We found that both UHI and urban cold islands (UCI) occurred among the eight cities during 2000–2014 (as measured by impervious surface area). Unlike what is generally considered, UHII in only three cities significantly decreased as EVI and ET increased ($p < 0.1$), indicating that the UHI or UCI cannot be completely explained simply from the perspective of the underlying surface. Increased vegetative cover (signaled by EVI) can increase ET, and thereby effectively mitigate the UHI. Each study station clearly showed that the underlying surface or vegetation affects urban-rural temperature, and that these factors should be considered during analysis of the UHI effect over time.

Keywords urbanization, evapotranspiration, urban cold island, background climate, air temperature

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1 Introduction

Urbanization alters Earth's terrestrial land surface, which can interact with regional climate (Grimm et al., 2008; Argüeso et al., 2014; Cui et al., 2015). The urban heat island (UHI) effect is a typical climate phenomenon whereby higher temperatures occur in urban areas than in surrounding rural areas. Due to global warming and urbanization, urban temperature is dually impacted by increases of regional background temperature and local human activities (Zhao et al., 2014). Urban areas have become ideal natural laboratories for studies on future climate effects due to the elevated temperatures where urban areas experience the UHI effect (Zhao et al., 2016).

The impacts of urbanization on temperature remains inconsistent because of various action mechanisms of different urbanization factors (Zhao et al., 2014). Based on current knowledge, the increased urban temperatures are caused by human activities, such as population aggregation, increased number of buildings, socio-economic development, and industrialization (Cui et al., 2016). Previous studies mostly characterized urban heat island intensity (UHII) and its driving factors in different cities, but the direct comparison of the UHII among different cities in different periods did not provide actual insight into or analysis of UHI mechanisms (Zhou et al., 2013; Cui et al., 2016; Luo and Peng, 2016). Some studies focused on analyzing the impacts of urban temperature on global warming (Kalnay and Cai, 2003; Peterson, 2003; Ren et al., 2008), but the contribution magnitude of UHI on global warming is currently a controversial issue (Fang et al., 2018). Although urban areas are undoubtedly warmer than surrounding rural areas in many cities, several studies concluded that the temperature trends in urban and rural areas were similar and the change of urban temperature was not significantly different from rural temperature (Peterson, 2003; Brohan et al., 2006; Jones et al., 2008). But a few other studies showed an opposite viewpoint (Kalnay and Cai, 2003; Ren et al., 2008; Piao et al., 2013). Furthermore, it seems that the urbanization effect on temperature can be easily understood when we analyze the relationship between temperature (both land surface temperature (LST) and air temperature), the expansion of urban impervious surfaces (Zhou et al., 2013, 2016), and other urbanization factors, such as population, urban size, urban landscape configuration, etc. (Clinton and Gong, 2013; Cui et al., 2016; Kamarianakis et al., 2017). However, when researchers compare the time series changes of urban temperature with rural temperature, there is no significant evidence that urban temperature is high enough to affect regional and global temperature (Peterson, 2003).

It is still a challenge to clarify the intrinsic impacts of underlying surface change on the UHI effect due to the complex factors and mechanisms. For now, the only conclusion confirmed is the warming effect of urban expansion (Zhou et al., 2013, 2016), but the reason is multi-factorial. Some studies concluded that UHI effect was primarily because of heat-storing structures, which increased the heat capacity in urban areas (Price, 1979; Roman et al., 2016). Some researchers believed that human activity and anthropogenic heat were the major contributors to UHI (Kusaka and Kimura, 2004; Argüeso et al., 2014). Increases in impervious surfaces and decreases in vegetative cover were also identified as factors that can increase urban temperatures by inhibiting cooling induced by evapotranspiration (ET) (Lynn et al., 2009; Imhoff et al., 2010; Li et al., 2011; Dong et al., 2015). However, following this logic, we cannot completely explain why the urban cold island (UCI, defined as the urban temperature below the rural temperature around an urban area) also appears in some cities (Yang et al., 2017). In other words, urbanization tends to be a linear, continuous process but urban temperature and UHII always fluctuates. In fact, even the UCI effect has not a physical basis (Parker, 2010). Stewart and Oke (2012) were aware of the conundrum and began to do research in an area near a meteorological station. A "local climate zone" classification method was developed by analyzing the actual land cover types of surrounding local field stations (Stewart and Oke, 2012). The mesoscale network of environmental monitoring stations (Mesonet) in Oklahoma (Brock et al., 1995; McPherson et al., 2007) also considers the local underlying surface types within a station's radius (within 5 km) to examine the underlying surface factors contributing to climate for that station.

When the impact of underlying surface on urban temperature is emphasized, urbanization can be conceptually divided into two opposing categories, namely a warming effect (urban expansion and intensification (UEI), human activities, etc.) and a cooling effect (vegetation expansion and intensification (VEI), wetlands and open water bodies expansion, etc.) (Hu et al., 2017). Prior studies on UHI effects and urban expansion always focused on dense impervious surface (including streets networks, building with concrete and steel) and sparse vegetation (Cui et al., 2012b; Guo et al., 2015). But after the elimination of natural vegetation and croplands for urban development, vegetation is often re-planted, fertilized, manicured, and irrigated (Li et al., 2011). That means during the urbanization process, UEI results in the increasing of impervious surface area, but urban vegetation may become well managed at the same time (Golubiewski, 2006). Moreover, with elevated temperature and atmospheric CO_2 concentration, the urban environment is suitable for vegetation growth (Walker et al., 2015; Zhao et al., 2016). Here UEI can be defined as the increasing of impervious surface areas, and the VEI can be defined as the comprehensive impacts of urban environment on vegetation. It has been confirmed that both urban impervious surface area and vegetation have a strong relationship with urban and rural temperature (Imhoff et al., 2010; Li et al., 2011; Cui et al., 2012a; Dong et al., 2015). Currently, many studies used normalized difference vegetation index (NDVI) as the indicator of vegetation abundance to analyze the relationship between vegetation and LST (Weng et al., 2004; Yao et al., 2018), while the other important vegetation index, enhanced vegetation (EVI) that can directly reflect the leaf information of vegetation is not fully used. Furthermore, although the UHI phenomenon was originally proposed using air temperature (Oke, 1973), remote sensing data is also widely used to investigate surface UHI (Weng et al., 2004; Li et al., 2017; Yao et al., 2018). Unlike the atmospheric temperature data observed at meteorological stations, remotely sensed LST data are often heavily affected by cloud, aerosols, water vapor, and other factors. Currently, mature algorithms for inversion of LST all face the inherent problem of optical remote sensing (Wan, 2008; Mildrexler et al., 2011), which will directly lead to vacancy and accuracy problems in detecting UHII, especially relatively weak UHII as the UHII and its dynamics may be less than the error range of the LST data itself. Therefore, a reliable observation dataset should be preferred to analyze UHII and its temporal changes. In addition, different from the clear effect of impervious surface, the role of vegetation is still somewhat uncertain (Weng et al., 2004). Among the various impact factors, the knowledge about the impact of vegetation on UHI during urbanization is still insufficient. Therefore, the relationship between vegetation and air temperature still need further exploration, especially at local scale (Dong et al., 2015; Mao et al., 2016).

In this study, we investigated the trends of urban and rural air temperature in the Great Plains region, in which urban vegetation usually depends on human management and the VEI and ET can clearly reflect the condition of vegetation. The study stations were in Oklahoma, USA, where the world-class Oklahoma Mesonet stations provide sufficient and accurate datasets for comparison of urban and rural stations. The main objectives of this study are to quantify the urban-rural temperature difference in various cities and to fully analyze and discuss the impacts of vegetation on urban-rural temperature difference in the dual context of local-scale urbanization and regional-scale atmospheric changes.

2 Materials and methods

2.1 Study area

The State of Oklahoma is in the south-central part of United States of America. The boundaries encompass 177.8×10^3 km^2 of land and 3.2×10^3 km^2 of water. The land is flat and almost all the state belongs to the Great Plains. Annual average precipitation in Oklahoma declines from east to west, and its climate mainly belongs to the cold semi-arid and sub-humid climate types (Kottek et al., 2006). In the southeastern region of the state, annual average temperature and precipitation can reach 17.0°C and 1020.0 mm, while in the northwest region, annual average temperature and precipitation are 14.0°C and 430 mm, respectively. Oklahoma contains 77 counties and more than 65% of Oklahomans live within metropolitan areas, or spheres of economic and social impact areas (Fig. 1). Grassland, farmland, and forests are three common land use and cover types in Oklahoma. Most of the urban areas are in the Cross Timbers and grassland ecoregions, except McAlester and Tahlequah. As for urban trees, Oklahoma Forestry Services recommends planting oak, maple, pine, redbud, soapberry, crabapple, and cypress.

2.2 Study data and data processing

2.2.1 Mesonet meteorological stations and its impact areas

The Oklahoma Mesonet is a world-class network of environmental monitoring stations which were designed and implemented by the University of Oklahoma and Oklahoma State University. The network has 121 stations covering the entire state, with at least 1 station in each county (Fig. 1). All the data are recorded automatically by instruments mounted on a tower ~10-meters in height, and air temperature is measured at the standard height of 1.5 m. The daily data from 2000 to 2014 is summarized and produced by Mesonet project partners. We averaged the daily air temperature data to calculate annual mean temperature. We also converted the original temperature

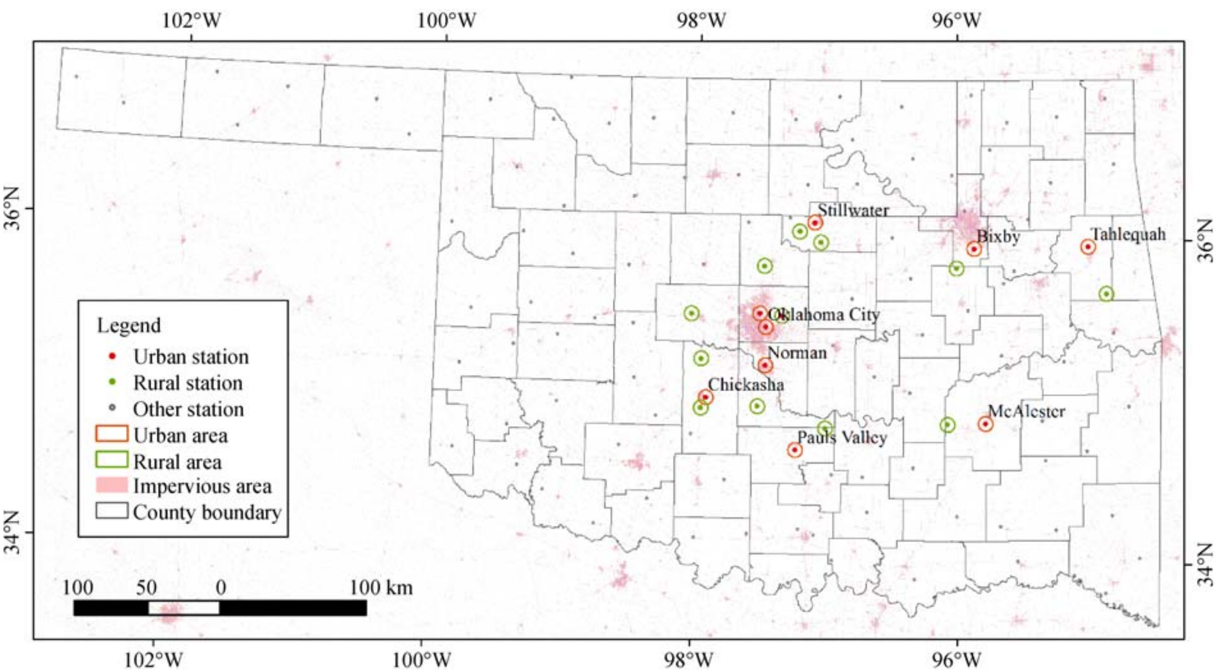

Fig. 1 Study area and stations. The red and cyan dots are the meteorological stations located in urban and rural areas, respectively. The red and cyan circles are 5 km buffer areas of each station. The red regions show the impervious surface areas in 2011.

(T) in Fahrenheit (°F) to Celsius (°C) by the formula:

$$T_{(°C)} = \left(T_{(°F)} - 32\right) \times 5/9.$$

The first step of data processing was to select and pair urban and rural Mesonet stations. An urban station selected must be located in an impervious area or in an urban area surrounded by impervious areas. And the corresponding rural stations were selected using considering altitude and distance from the urban station. The nearest station with altitude difference of less than 100 m to an urban station was the paired rural station. In total, eight cities with 9 urban stations and 12 rural stations were chosen (Table 1). Oklahoma City was the only city in which two urban stations were chosen, each of which was paired with two rural stations. All other urban stations were paired with 1 rural station, except for Stillwater.

Finally, to define the observational footprint of a station, we followed the station information provided by Mesonet and set a 5 km buffer around each station to analyze the relationship between underlying surfaces (Zhang et al., 2004b; Cui et al., 2016) and air temperature. These buffers capture the main observational footprint of each station, the underlying surface of which have key impacts on air temperature. Among them, only the buffer of CHIC overlaps slightly with the buffer of NINN. All eight cities are in the US Great Plains, which provides a good test area to focus on analyzing the impact of urban development within 5 km buffer of a station on temperature and reduces the impacts caused by other factors, such as greenhouse gas, etc.

Some Mesonet stations (e.g., OKCE and NRMN) did not have consistent data from 2000–2014. Therefore, this study only analyzed corresponding interannual variations of temperature and vegetation for stations with continuous observational data. We used the difference value of "urban temperature minus rural temperature" to represent the UHII (positive value) and UCII (negative value).

2.2.2 Urban impervious surface data

Using the percentage of developed (imperviousness) land data (National Land Cover Database NLCD) from America Multi-Resolution Land Characteristics (MRLC) consortium in 2001 and 2011, we analyzed the UEI within the 5 km buffer areas of the 21 Mesonet stations from 2001 to 2011. The data can be directly downloaded from MRLC consortium's official website.

2.2.3 Vegetation index and evapotranspiration data

We used MODIS products to analyze vegetation variation within the 5 km buffer areas of each meteorological station. The Enhanced Vegetation Index (MOD13A3, EVI) with a spatial resolution of 1 km was used to observe greenness of vegetation, and we evaluated the relationship between EVI and air temperature. The EVI data minimizes canopy background variations and improved sensitivity over high vegetation conditions. MODIS ET datasets (MOD16A2) with a spatial resolution of 1 km were used to evaluate the impact of ET on air temperature. The ET algorithm is based on the Penman-Monteith equation. The ET data includes evaporation from wet and moist soil, from rain water intercepted by the canopy before it reaches the ground, and the transpiration through stomata on plant leaves and stems (Mu et al., 2007). It should be noted that some ET grid cells in urban areas have a null value. In this study, very few grid cells with null values in the buffer areas of individual urban stations were considered as purely impervious surfaces and were assigned as a value of 0. The EVI and ET datasets can be accessed from Land Processes Distributed Active Archive Center (LP DAAC, https://lpdaac.usgs.gov/

Table 1 The basic station information within 5 km at the eight cities. All the station information comes from Oklahoma Mesonet

City	Urban station			Rural station		
	Name	Altitude/m	Major climate regulations	Name	Altitude/m	Major climate regulations
Oklahoma City	OKCN	362	Grasslands/Herbaceous	SPEN	373	Grasslands/Herbaceous
				ELRE	419	Grasslands/Herbaceous
	OKCE	355	Grasslands/Herbaceous	GUTH	330	Grasslands/Herbaceous
				MINC	430	Grasslands/Herbaceous
Tulsa	BIXB	184	Cultivated Crop	HECT	243	Pasture/Hay
Norman	NRMN	357	Grasslands/Herbaceous	WASH	345	Pasture/Hay
Stillwater	STIL	272	Grasslands/Herbaceous	MARE	327	Grasslands/Herbaceous
				PERK	292	Cultivated Crop
Tahlequah	TAHL	290	Pasture/Hay	COOK	299	Pasture/Hay
McAlester	MCAL	230	Grasslands/Herbaceous	STUA	256	Pasture/Hay
Chickasha	CHIC	328	Cultivated Crop	NINN	356	Developed Low Intensity
Pauls Valley	PAUL	291	Developed Open Space	BYAR	345	Pasture/Hay

data_access/). EVI and ET data were also averaged to obtain annual mean values.

3 Results

3.1 Inter-annual variations of urban and rural temperature

Both UHI and UCI effects coexisted in the eight cities. As the most populous city in the state, Oklahoma City had the largest UHII with a value of 0.58°C. Conversely, the urban temperatures in Tulsa, Tahlequah, and Chickasha were less than rural temperatures, showing an UCI effect (Fig. 2). Surprisingly, as the second most populous city, Tulsa had the largest UCI intensity (UCII), but the value of UCII increased over time, with an average annual rate of –0.38 during 2000–2014.

Furthermore, we used the linear trend method to check temperature and UHII variations over time. The results showed that the temperature recorded by four urban areas and four rural areas decreased from 2000 to 2014 (Table 2). The remaining four urban stations recorded a slight increasing trend for the past 15 years. Although the UCI still appeared in some cities, almost all these cities showed that the UHII increased slightly (or UCII decreased) with a mean trend of 0.0003°C·yr^{-1}. In a direct comparison of the trends of urban temperature with rural temperature, we found that the temperature trends in rural areas were always less than that in urban trends except McAlester and Oklahoma City. Additionally, the maximum and minimum UHII trends appeared in Tulsa and Oklahoma City, respectively. Correspondingly, Tulsa had the maximum urban expansion ratio, while Oklahoma City had the second minimum urban expansion ratio, implying that the other factors still play a role of affecting urban temperature.

3.2 The relationships between UHII and background temperature

Urban and rural temperature changes are highly synergistic. Figure 2 showed a significant relationship between urban temperature and rural temperature ($p < 0.1$) very likely because of the likeness of regional temperature and spatial autocorrelation. However, the differences of inter-annual variation between urban temperature and rural temperature still existed, showing that the impact of UEI to a certain extent.

To further check the relationship between regional temperature and urban temperature, we used linear regression of rural temperature versus the UHII. Here we observed the scatterplot of rural and UHII trends in the eight cities (Fig. 3). It was clear that UHII or UCII obviously decreased along with the rural warming in six cities (failing to pass significance test of 0.1 but passing significance test of 0.5). It seems that the difference value between urban and rural temperature tended to lessen over time under a warming background (signaled by rural temperature). However, a decreasing trend was not observed in Norman or McAlester (Fig. 3). Moreover, the negative relationship between background temperature and UHII indicated that the variation of UHII was very different than urban temperature under the background climate conditions (rural temperature).

3.3 The relationships between vegetation and urban temperature and UHII

Averaged impervious surface areas in buffers of urban stations continuously increased from 11.13% in 2001 to 13.06% in 2011, while the averaged impervious surface areas in buffers of rural stations marginally increased from

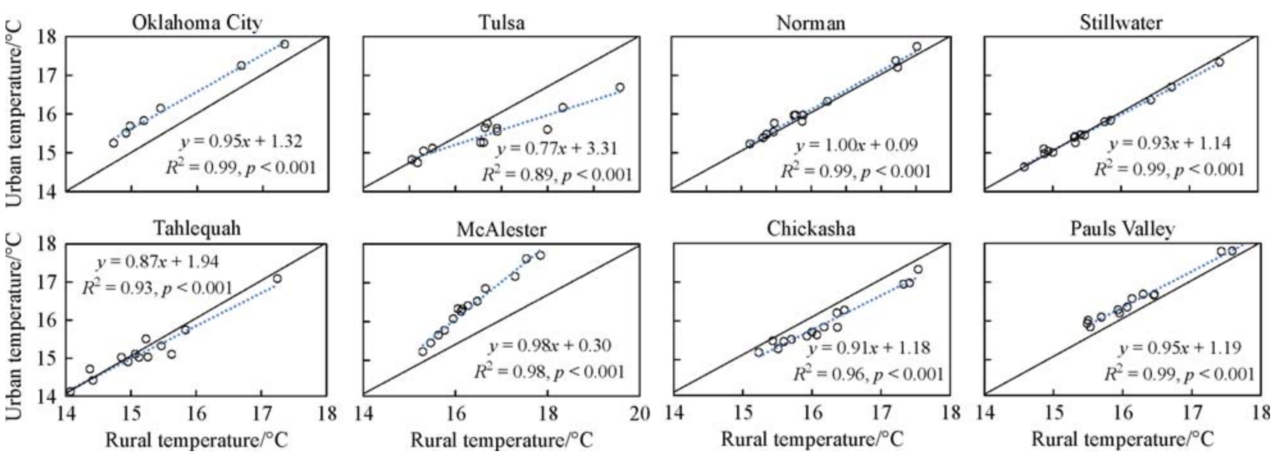

Fig. 2 The relationship between urban temperature and rural temperature at the eight cities. Blue dotted lines indicate the linear fitting lines over time; black lines mean the "$y = x$" lines.

Table 2 The annual linear trends (slope) of temperature, EVI, and ET from 2000 to 2014, and percentage of impervious surface for urban and rural stations in 2001 and 2011. ΔEVI and ΔET is the trend difference between EVI or ET for urban and rural areas ($EVI_{urban} - EVI_{rural}$; $ET_{urban} - ET_{rural}$). All the value is the trends over time (year) accordingly except the urban impervious percentage (*) in 2001 and 2011

City	Temperature trend/(°C·yr^{-1})			EVI trend			ET trend/(mm·yr^{-1})			Impervious surface percentage/%*			
	Urban	Rural	UHII	Urban	Rural	ΔEVI	Urban	Rural	ΔET	Urban 2001	Rural 2001	Urban 2011	Rural 2011
Oklahoma City	–0.007	0.021	–0.028	0.003	0.002	0.000	–4.149	–3.106	–1.043	29.07	1.76	32.26	1.85
Tulsa	–0.032	–0.060	0.028	0.000	0.000	0.000	–0.719	–1.649	0.930	5.27	0.72	8.01	0.76
Norman	0.018	0.009	0.001	–0.001	0.000	–0.001	–3.232	–1.406	–1.826	24.26	0.15	29.21	0.15
Stillwater	0.009	0.004	0.005	–0.001	–0.001	0.000	–2.635	–2.393	–0.242	12.58	0.98	14.54	1.12
Tahlequah	0.007	–0.004	0.011	0.000	–0.001	0.001	–2.718	1.143	–3.860	0.86	0.12	1.09	0.12
McAlester	–0.028	–0.006	–0.021	–0.001	0.000	0.000	–1.971	–3.582	1.610	3.81	0.26	4.80	0.33
Chickasha	–0.004	–0.010	0.006	0.000	0.000	–0.001	–1.410	–1.223	–0.187	8.66	1.25	9.50	1.33
Pauls Valley	0.001	0.001	0.000	–0.001	0.001	–0.002	–4.212	–0.647	–3.565	4.49	0.43	5.07	0.44

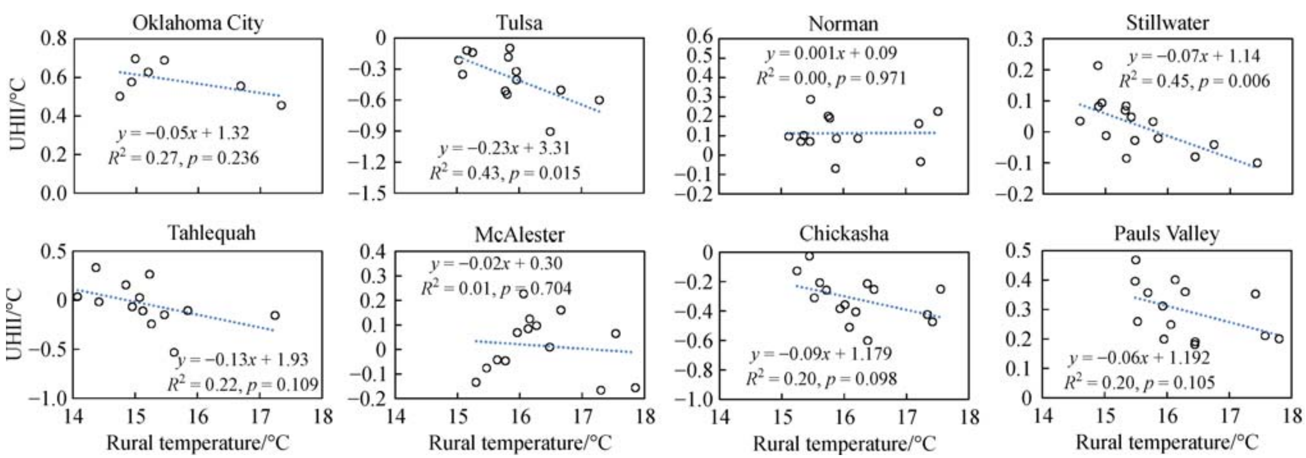

Fig. 3 The relationship between temperature trends of UHII and rural temperature in the eight cities from 2000 to 2014.

0.71% in 2001 to 0.76% in 2011 (Table 2). Both the proportion of the original impervious surface areas and their increase ratios in buffers of urban stations are larger than that in buffers of rural stations. Correspondingly, the pervious surface areas, which mainly were composed of vegetation, in urban areas were always less than that in rural areas. However, urban temperature did not follow only the variation of urban expansion but had comparatively independent variability due to the compounding effects of vegetation or others urbanization factors (including urban expansion). To examine the impacts of VEI on temperature variation, we compared the trends of urban temperature and UHII with EVI in the eight cities.

The trends of urban EVI in the 8 cities were very small and no trends were observed in Tulsa, Tahlequah, and Chickasha (Table 2). The trends in EVI for Stillwater, McAlester, Pauls Valley, and Norman slightly decreased with the value of –0.001. Oklahoma City showed an increasing trend, indicating that it was possible to keep a stable EVI despite increases in UEI. We also chose ΔEVI (the difference in EVI between urban and rural areas) to explore the impact of vegetation on UHII or UCII (Fig. 4, lower panel). The range of ΔEVI trend in the eight cities was from –0.002 to 0.001 (Table 2). However, only five cites showed a negative relationship between ΔEVI and UHII and the only statistically significant relationships ($p < 0.1$) seen were for Tulsa and Tahlequah (Fig. 4, lower panel).

To check the cooling effect of vegetation on urban temperature and UHII or UCII, we used ET and ΔET to explore the impact of ET on temperature. Figure 5 showed that urban ET was less than rural ET for most cities. The negative ΔET trends illustrated the increased impact of extending impervious surface areas on urban ET (Table 2). Furthermore, the simple linear regression analysis clearly showed that both ET and EVI had negative correlation with urban temperature (Figs. 4 and 5). More specifically, the statistically significant relationship ($p < 0.1$) between urban temperature and urban ET for six cities showed the effective cooling effect of urban ET on urban temperature (Fig. 5, upper panel). In terms of UHII, the relationship between ΔEVI and UHII showed that ΔEVI

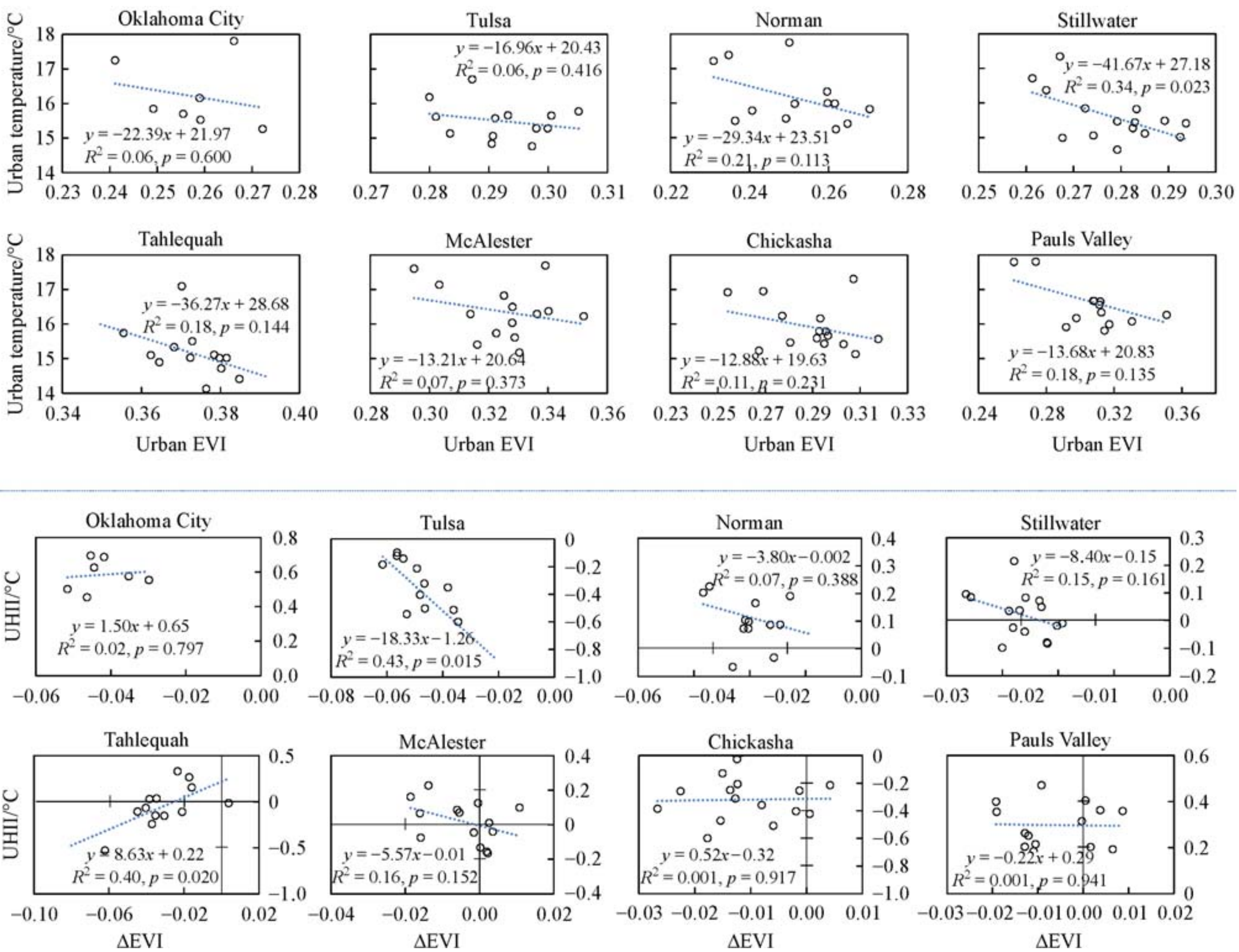

Fig. 4 The relationship between annual mean EVI and urban temperature, and between ΔEVI ($EVI_{urban} – EVI_{rural}$) and UHII or UCII in the eight cities from 2000 to 2014.

cannot be used to interpret the dynamics of UHII due to other complex variables in each city (Fig. 4). However, ΔET still showed an obviously negative correlation in five cities (Fig. 5, lower panel). It further suggests a direct cooling effect of ET.

4 Discussion

4.1 Station location and station temperature

Analysis of the impact of urbanization on a changing climate at the global or regional scale is difficult (Peterson, 2003; Jones et al., 2008; Liu et al., 2014). However, human activities are certainly concentrated in urban areas. If we consider the horizontal impacts of other background variables, like CO_2 concentration, atmospheric circulation, etc., then the impact of urbanization should not to be neglected (Churkina, 2016; Zhou et al., 2016). We cannot totally distinguish the effect caused by urbanization and other background changes in urban areas because meteorological stations at a certain distance from urban areas are likely to suffer the same impacts of both urbanization and other non-urbanization factors. Some of the urbanization factors that trigger warming in parts of an urban area are also present in rural areas (Peterson, 2003). But the impacts of background changes should be excluded as much as possible so that we can focus on the impact of underlying surface change on temperature. There are more open areas in small and medium-sized cities than megacities. We assume these eight cities receive similar impacts as do urban and rural areas, and they can effectively avoid some of the complex impacts caused by horizontal turbulence (Bang et al., 2010; Hutyra et al., 2014; Haashemi et al., 2016).

Land surface interacts with air temperature, especially within the lower few thousand meters of the atmosphere, thereby influencing local and regional climatic properties (Chandler, 1976). At the local scale, the underlying surface surrounding a meteorological station has a major impact on the observed temperature (Stewart and Oke, 2012; Hu et al., 2017). In this study, all the instruments used to measure temperature are fixed at 1.5 m above ground on Mesonet towers. The footprint of 1.5 m sensors may be a few tens of meters in neutral conditions, smaller when atmosphere conditions are unstable, and larger when it is stable (Schmid et al., 1991; Oke, 2004; Stewart, 2011). Therefore, the land surface at local scale plays a vital role for *in situ* temperature, especially in small cities (Piao et al., 2013; Zhao et al., 2014; Hu et al., 2017). However, the relationship between station and their representative areas (point and polygon) is an issue that has always existed in remote sensing research. The introduction of "footprint" provides a way to quantify the source areas of a station, but the footprint is variable over space and time. At the interannual scale, due to the impacts of many meteorological variables such as prevailing winds etc., it is difficult to know the exact size and shape of the footprint at any given time. The rule we can infer may be that the further the distance away a station, the poorer the representativeness of a station. In this study, we directly used 5 km as an impact radius of a station based on others' study (Liu et al., 2011). When Mesonet provided the observation data, they also provided an introduction document containing the surface cover conditions (named as major climate regulations) within 5 km areas of all the stations (Table 1). It is true that 5 km does not consider the footprint of a field station. This is a deficiency and assumption of this study.

Our results show that UHI and UCI coexist in the eight cities, although urban stations usually experience more warming effects due to urbanization (Fig. 2). The maximum impervious surface is less than 35% (Table 2), and the corresponding vegetation area is always more than impervious surface within a buffer, showing that as the important factors of underlying surface, impervious surface and vegetation together regulated the result of UHI or UCI in a city at the local station (Stewart and Oke, 2012; Heusinkveld et al., 2014). It seems that regional conditions most directly impact the overall temperature values of both urban and rural stations, but the local underlying surface decides the specific temperature variation of a station (Chandler, 1976; Stewart and Oke, 2012; Zhao et al., 2014; Hu et al., 2017).

4.2 The trend differences between urban and rural temperature

The most reliable way to investigate possible temperature biases affected by urbanization is to compare rural and urban station data over time (Brohan et al., 2006). As mentioned in previous sections, some high or low temperatures within a city cannot be captured due to the relatively small footprint of the urban Mesonet stations. Indeed, LST data has been widely used to research the UHI effect (Peng et al., 2012; Bokaie et al., 2016; Cui et al., 2016; Jenerette et al., 2016; Liu et al., 2016). In contrast to LST data, air temperature can be perceived directly by individuals. In addition, LST data has more null grids with unfixed location due to the impact of clouds and shadows. It is difficult to do a long-time series analysis (Hu and Brunsell, 2013). Maybe such an analysis can be conducted after interpolation, but the precision is hard to guarantee, especially when the UHI signals are weak in small and medium-sized cities.

With the observed air temperature, our results clearly show that UHII or UCII is small in the eight small and medium-sized cities. Even in Oklahoma City, the annual UHII is 0.58°C. Previous studies demonstrated that the daily temperature within urban core was 0.5°C and nightly temperature was 2.0°C warmer than rural areas during an intense heat wave period (Basara et al., 2010). The trends of urban and rural temperature are also relatively small (0.0003°C, Table 2) but different in the eight cities. Our results were similar with some previously published results (Peterson, 2003; Jones et al., 2008). However, the similar trends may be due to the varying proximity of the urban and rural stations we paired for this study, it cannot be interpreted that the urbanization has no-significant impact on background temperature and our findings clearly indicate that the trend of urban temperature is greater upward than rural temperature (UHII > 0) in most cities. Contrary to general expectations, UHII decreases as the background temperature increases (Fig. 3). The finding indicates that UHIIs tend to be stable and even decrease under regional background warming, and it may imply that the effect of UHII may be reduced in the future. However, there were inconsistent results for two cities (Norman and McAlester). Given that the station temperature cannot reflect the local high temperature often occurring in urban core, the entire variation of UHII in urban areas needs further analysis.

4.3 The cooling effect of vegetation intensification

The processes of UHII varies with latitude, climate, topography, and meteorological conditions (Haashemi et al., 2016). From a perspective of heat energy exchange and diffusion, temperature can be impacted by vertical and horizontal thermal circulation. Horizontal impacts mainly take into account the atmospheric turbulence and transmission within a region (Eliasson, 1996; Cui et al., 2015). It is very complex and must be simulated by regional climate models (Cui et al., 2015). Even so, the input variables do not adequately reflect the indirect impacts of all factors such as the greenhouse gases, the interruption on light and wind conditions caused by roadways, human activities and industry, convection, and circulation (Bang et al., 2010; Lietzke and Vogt, 2013; Hutyra et al., 2014). As to the vertical impacts, they mainly come from differences in the energy budget caused by land surface and anthropogenic factors (Oke, 2004). The construction of urban areas and human activities result in a dramatically alteration of land

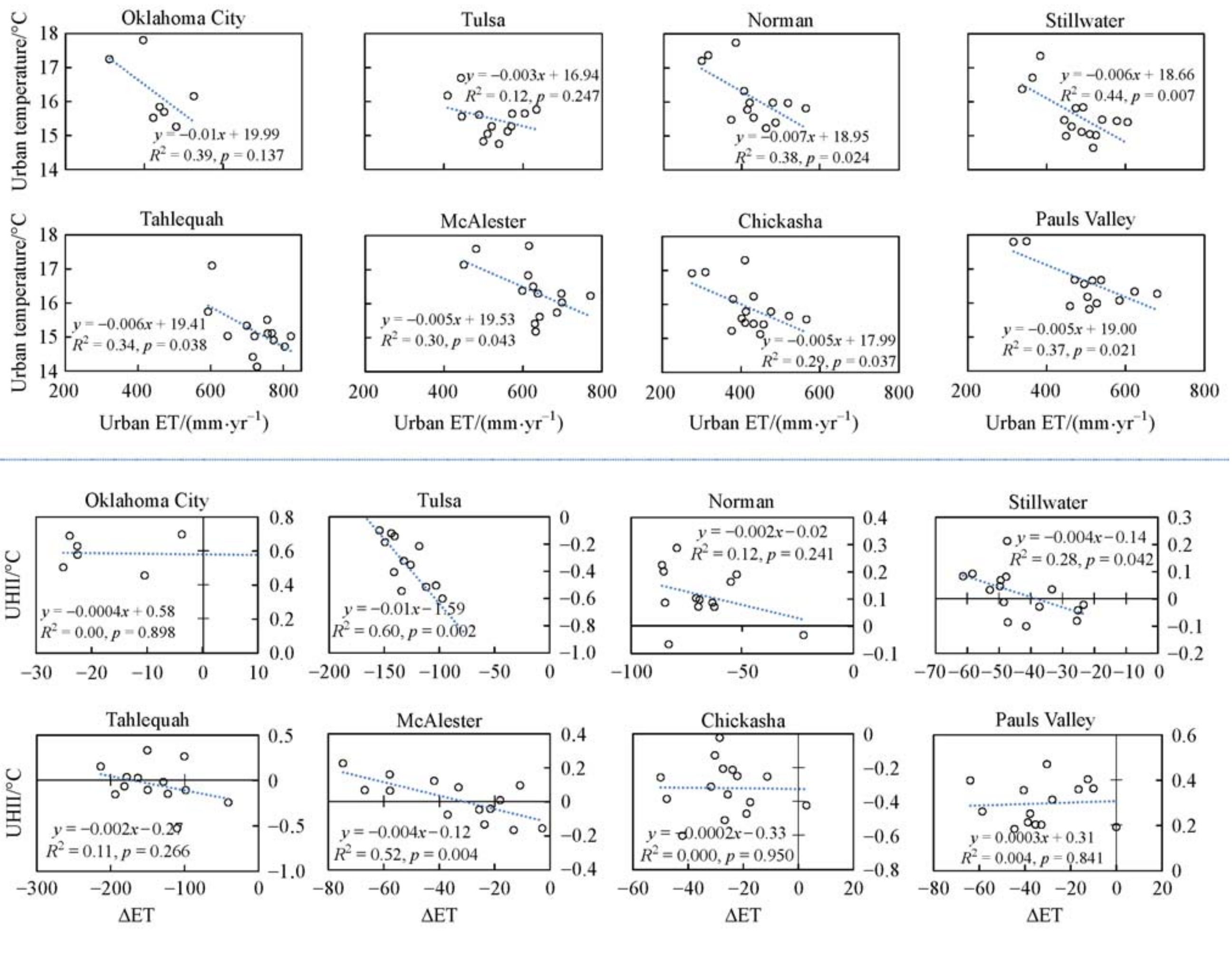

Fig. 5 The relationship between annual mean ET and urban temperature, and between ΔET ($ET_{urban} - ET_{rural}$) and UHII or UCII in the eight cities from 2000 to 2014.

surfaces and energy flows in and around urban areas (Chandler, 1976). Vertical effects contain the impacts of both UEI and vegetation intensification.

Urban and vegetation expansion and intensification (UEI/VEI) are two aspects of urbanization and affect the land surfaces around a meteorological station and within a buffer (Fig. 6). The process of urbanization, on one hand, increases impervious surface and decreases vegetation areas, thereby causing the urban areas to have more sensible energy than their rural areas (Cui et al., 2012a). On the other hand, introduced and well-managed urban vegetation can encourage plant growth and increase EVI, thereby reducing the urban temperature (Li et al., 2011; Qiu et al., 2013; Guo et al., 2015; Cui et al., 2017). Greenspace has been observed to increase in areas previously covered by impervious surfaces (Qian et al., 2015). The warming effect of impervious surfaces has been relatively clear, but the relationship between vegetation and UHI is complex (Weng et al., 2004). Compared to vegetation indexes, ET can explain the impact of vegetation on temperature directly and obviously (Zhao et al., 2018). During the process of increasing impervious surfaces, more bare lands are covered by regular and well-managed vegetation (Figs. 6(a), 6(b), 6(e), and 6(f)). Figures 6(c) and 6(d) clearly show that vegetation decline is delayed and the growth period of vegetation in urban areas is extended by urbanization and human management, compared with natural vegetation in rural areas. So, in this sense, just taking notice of UEI or VEI is unilateral while the climatic effects of urbanization are bi-lateral. The UEI and VEI effect on temperature should be the main regulation factors and drivers to UHI or UCI. Urban vegetation may experience enhanced growth periods and carbon uptake since the urban vegetation typically receives more irrigation, fertilization, higher temperatures, and longer growth season (Imhoff et al., 2004; Zhang et al., 2004a; Golubiewski, 2006). Urban landscaping, the most common greening action in cities, is quite significant in the aspect of reducing warming effects of urbanization (Watts et al., 2015). By absorbing heat or shading impervious surfaces, vegetation plays a substantial role in reducing the urban temperature (Wong et al., 2003; Steeneveld et al., 2011; Qiu et al., 2013). In this study, despite the continuous reduction in total vegetative area in urban areas, the temporal stability of vegetation greenness measured by EVI suggested that urban vegetation has been well managed in all the eight cities and continues to age (Table 2). For instance, increases in EVI over time can indicate more complex canopies in addition to increases in leaf area. Furthermore, vegetation produces a cooling effect mainly through ET (Zhao et al., 2018), but the analysis results of ET show that the negative impact of increased impervious areas may be hard to be offset by vegetation management in urban areas. No matter the warming effect driven by urbanization or the cooling effect induced by vegetation intensification, only one net effect can be shown in a city. Our results illustrated that temperature differences between urban and rural areas in

Fig. 6 The urban/vegetation expansion and intensification (UEI/VEI) in an urban area. Human-managed vegetation in urban areas: (a) introduced plants; (b) irrigation; (c) natural vegetation decline in winter; and (d) urban vegetation growth in winter (Oklahoma, December 9, 2016), possibly due to irrigation and UHI. The comparison of (e) to (f) demonstrates the coexistence of increases in UEI and VEI. The two photos were taken in August 2003 and September 2016 and accessed via Google Earth.

six cities of the eight cities had an increasing trend and two did not (Table 2), suggesting that the cooling effect of VEI may have offset the warming effect of urbanization. However, other impact factors, such as background environment and climate conditions still play an important role at the local or regional scales. We cannot distinguish or mask their effect although the Great Plains cities may receive the equivalent effects in urban and paired rural areas at times. The factors that drive UHI or UCI thus needs more studies in future.

5 Conclusions

In this study, we compared and analyzed variations in temperature for urban and rural Mesonet stations, as well as the cooling effect of VEI in eight Great Plains cities. We found that the urban heat or cold island effect was present in each of the eight cities and underlying surface types play an essential role in regulating the station temperature. In addition, we found that UHII decreased as the increasing of rural temperature in six cities, but more studies should be scrupulously done to verify preliminary results in the future.

UEI and VEI affected the urban temperature through warming and cooling, respectively. Urban expansion, measured by impervious surfaces, increased over time. Correspondingly, vegetation intensification, measured by EVI and ET, mitigated the UHI. Urban vegetation greenness demonstrated a strong temporal stability, but evapotranspiration continuously decreased during impervious surface expansion. Overall, urban vegetation played a great role in cooling urban temperatures. The integrated result also showed that the warming effect of UEI and other urbanization factors were dominant compared to the cooling effect of vegetation intensification. Although vegetation showed a cooling effect, the other factors still cannot be ignored for interpreting the UHI phenomenon in each city. The role of underlying surfaces and vegetation should not be overestimated in the determination of differences in urban and rural temperature. However, the other factors of non-underlying surfaces impacting urban temperatures needs further study.

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