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3	Analysis of Urban Effects in Oklahoma City using a Dense Surface Observing Network
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Abstract

Many studies have investigated urban heat island (UHI) intensity for cities around the 29 world, which is normally quantified as temperature difference between urban location(s) and 30 31 rural location(s). A few open questions still remain regarding UHI, such as the spatial distribution of UHI intensity, temporal (including diurnal and seasonal) variation of UHI 32 intensity, and the UHI formation mechanism. A dense network of atmospheric monitoring sites, 33 known as the Oklahoma City (OKC) Micronet (OKCNET), was deployed in 2008 across the 34 OKC metropolitan area. This study analyzes data from OKCNET in 2009 and 2010 to 35 36 investigate OKC UHI at a sub-city spatial scale for the first time. The UHI intensity exhibited large spatial variations over OKC. During both daytime and nighttime, the strongest UHI 37 intensity is mostly confined around the central business district (CBD) where land surface 38 roughness is the highest in the OKC metropolitan area. These results do not support the 39 roughness warming theory to explain the air temperature UHI in OKC. The UHI intensity of 40 OKC increased prominently around the early evening transition (EET) and stayed at a fairly 41 constant level throughout the night. The physical processes during the EET play a critical role in 42 determining the nocturnal UHI intensity. The near-surface rural temperature inversion strength 43 44 was a good indicator for nocturnal UHI intensity. As a consequence of the relatively weak nearsurface rural inversion, the strongest nocturnal UHI in OKC was less likely to occur in summer. 45 Other meteorological factors (e.g., wind speed, cloud) can affect the stability/depth of nighttime 46 47 boundary layer, and can thus modulate nocturnal UHI intensity.

48 Keywords: urban heat island, urban observation network, micrometeorology

49 **1. Introduction**

Due to the different properties of urban surface, temperatures over urban areas are 50 typically higher than over the surrounding rural areas, a phenomenon well known as the urban 51 heat island (UHI; Oke 1976, 1981, 1982; Arnfield 2003). During the past few decades, many 52 studies have been conducted to observe and document UHI magnitude/intensity in cities around 53 54 the world. UHI intensity is often quantified as the difference in temperature of near-surface air or land surface between urban site(s) and surrounding rural site(s). Most of these previous 55 studies were limited to discuss pairs of urban-rural differences, either difference between one 56 57 urban and one rural site or between urban mean and rural mean temperature (e.g., Gedzelman et al. 2003; Wienert and Kuttler 2005; Yow and Carbone 2006; Alonso et al. 2007; Basara et al. 58 2008; Miao et al. 2009; Steeneveld et al. 2011; Husain et al. 2014; Hu and Xue 2015). 59

Compared to its temporal characteristics, the spatial characteristics of UHI intensity 60 (UHII) are much less investigated, largely due to difficulties and costs of deploying multiple 61 instruments with enough density across the urban area (Basara et al. 2010; Chapman et al. 2015). 62 Because the in-situ weather stations in urban areas are usually sparse (Kim and Baik 2005; Stone 63 2007; Tan et al. 2010; Basara et al. 2011; Muller et al. 2013; Fenner et al. 2014), UHII at the 64 65 spatial scale of a city is sometimes derived from remotely sensed land-surface temperatures (Voogt and Oke 2003; Fung et al. 2009; Nichol et al. 2009; Zhou and Shepherd 2010; Peng et al. 66 2012; Winguth and Kelp 2013). However, there are inherent issues associated with remotely 67 sensed UHII. Satellite-derived land-surface temperature only account for the radiant 68 temperatures of surfaces seen by the radiometer and the data correspond to averages across the 69 70 area of a pixel (Roth et al. 1989). As a consequence, roofs, treetops, and open horizontal areas 71 are oversampled and vertical surfaces and areas below tree crowns are neglected in remotely 72 sensed UHII. The physical properties, and radiative and turbulent environments of facets that are well represented by remote-sensing data often differ from those that are undersampled (Arnfield 73 2003). Thus, the remote sensing poorly sample the true surface temperature within the city. As 74 a result, remotely-sensed land-surface temperature UHII and in-situ measured air temperature 75 UHII can have very distinctly different behaviors, such as, different diurnal variation (Cui and de 76 77 Foy 2012). While air temperature UHII is reported to be stronger at night than in the day in many studies (Arnfield 2003; Souch and Grimmond 2006), remotely-sensed land-surface UHI shows 78 stronger intensity during daytime than during nighttime (Roth et al. 1989; Imhoff et al. 2010; 79 80 Schwarz et al. 2011; Jin 2012; Klok et al. 2012; Peng et al. 2012; Zhao et al. 2014). Thus, further investigation of spatial and temporal characteristics of UHII using consistent, quality 81 observations of air temperature is required to improve the understanding of the impacts of 82 urbanization (Bottyan and Unger 2003; Grimmond 2006; Huang et al. 2008; Basara et al. 2010; 83 Grimmond et al. 2010; Chen et al. 2012; Muller et al. 2013; Schatz and Kucharik 2014; Dou et 84 al. 2015). The information regarding spatial distribution of air temperature UHI of a city can 85 also help provide heat information at a neighborhood scale for use in future detailed public 86 health analyses and heat hazard mitigation strategies (Heusinkveld et al. 2014; Chapman et al. 87 88 2015; Debbage and Shepherd 2015).

89 Several studies have shown that UHII is dictated by the intrinsic characteristics of a city 90 (Oke 1981, 1982; Unger 2004; Grimmond 2007; Hart and Sailor 2009; Georgakis et al. 2010; 91 Ryu and Baik 2012; Adachi et al. 2014; Barlow 2014) and modulated by external meteorological 92 factors (Morris and Simmonds 2000; Hu et al. 2013c). Oke et al. (1991) used a simple energy 93 balance model to assess the relative importance of the commonly stated intrinsic causes of UHI 94 under calm and cloudless conditions, including anthropogenic heat, thermal properties/moisture

availability of the materials of the city, street canyon geometry, and urban greenhouse gases. The 95 first three of these were identified as the main intrinsic causative factors contributing to the UHII 96 in a modeling study conducted by Ryu and Baik (2012). A quantitative attribution of various 97 contributions to UHII is estimated in Zhao et al. (2014) using a surface energy-balance analysis. 98 Low efficiency at dissipating heat from urban surfaces due to larger aerodynamic resistance is 99 100 diagnosed to be the dominant contributor to daytime UHII in cities in the humid southeast and south-central United States (including Oklahoma), which coincides roughly with the Koppen-101 Geiger temperate climate zone. Improved understanding of causative factors contributing to the 102 103 UHII is still needed for UHI mitigation management (Hidalgo et al. 2010; Loughner et al. 2012; 104 Clinton and Gong 2013; Li et al. 2013; Theeuwes et al. 2013; Li et al. 2014; Zhao et al. 2014).

Conflicting results have been reported for the seasonal variation of UHII (Arnfield 2003; 105 106 Yang et al. 2013). Using the air temperature defined UHI, some previous studies (e.g., Magee et al. 1999; Steinecke 1999; Montavez et al. 2000; Jonsson 2004; Kim and Baik 2005; Hinkel and 107 Nelson 2007; Zhou and Shepherd 2010; Memon et al. 2011; Yang et al. 2013) reported that UHIs 108 109 are the weakest in summer and strongest in winter; while other studies found that UHIs are best developed in summer or warm half of the year (Karl et al. 1988; Schmidlin 1989; Klysik and 110 111 Fortuniak 1999; Philandras et al. 1999; Morris et al. 2001; Fortuniak et al. 2006; Camilloni and Barrucand 2012; Fenner et al. 2014; Schatz and Kucharik 2014; van Hove et al. 2015). Most 112 113 studies based on analysis of satellite-derived land-surface temperature reported that UHII over 114 many cities was significantly higher in summer than in winter, e.g., Imhoff et al. (2010) and Peng et al. (2012) for cities of the United States, Wang et al. (2007a) and Zhang et al. (2005) for 115 Beijing, Li et al. (2012) for Shanghai, Meng and Liu (2013) for Jinan, Zhang et al. (2010) for 116 117 other cities. Factors governing the seasonal variation of UHII need further investigation.

118 Oklahoma City (OKC), Oklahoma (35.468 762°N, 97.516 304°W), spans ~1610 km². It 119 is one of the 10 largest cities by land area in the United States. The terrain of OKC is quite flat. The temporal variation of UHII in OKC has been investigated in observational studies (Basara et 120 121 al. 2008; Basara et al. 2010; Klein 2012) for a few short-term periods (mostly for July 2003). Studies with research and weather prediction models further focused on evaluating the skill of 122 these models in predicting UHII with urban canopy-layer parameterization schemes of different 123 level of complexity (Liu et al. 2006; Lemonsu et al. 2009; Hu et al. 2013c; Husain et al. 2013). 124 During 2007 and 2008, a dense network of atmospheric monitoring sites (i.e., the OKC Micronet 125 or OKCNET) was deployed across the OKC metropolitan area (Basara et al. 2011), which 126 provided data for long-term monitoring of UHII in OKC at the spatial scale of the city. Thus, 127 given the dense meteorological observations across the OKC metropolitan area, the objectives of 128 129 this study are to (1) illustrate the spatial pattern of UHII in the OKC metropolitan area, (2) investigate the diurnal and seasonal variations of UHII in OKC, and (3) diagnose how UHI 130 formation is related to land-surface and boundary-layer processes. Since previous studies have 131 132 shown that UHII is closely related to wind speed (Fast et al. 2005; Hu et al. 2013c), some of its spatiotemporal characteristics are also discussed. 133

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135 **2. Data and methods**

Our analysis focuses on the OKC metropolitan area (Fig. 1). Embedded within the OKC urbanized area is a well-defined central business district (CBD) that spans ~20 km², with the average building height being around 50–70 m and the tallest building being 152 m high (during the years studied). This study utilized surface meteorological data collected at the stations 140

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around the OKC metropolitan area from two networks, i.e., the OKC Micronet (OKCNET) and the Oklahoma Mesonet (site locations in Fig. 1) (Brock et al. 1995; McPherson et al. 2007).

142 The OKCNET is an operational network designed to improve atmospheric monitoring 143 across the OKC metropolitan area, which was officially commissioned in November 2008 (Basara et al. 2011). OKCNET consists of a total of 39 stations with an average spacing of 144 145 approximately 3 km, including 36 stations mounted on traffic signals at a height of ~9 m above ground level (AGL) and 3 stations in OKC (i.e., OKCN, OKCW, and OKCE) deployed 146 following the protocols of the Oklahoma Mesonet. Basara et al. (2010, 2011) provided detailed 147 148 information about the siting of the OKCNET sites and their classification using different criteria proposed in the literature. Basara et al. (2010) used a simplified classification for a composite 149 analysis of UHI in OKC for a heat wave episode, in which OKCNET sites are grouped into three 150 151 categories (i.e., urban, suburban, and rural) based on the surrounding land cover characteristics. A more detailed climate-based classification of urban sites, i.e., seven urban climate zones 152 (UCZs), was proposed by Oke (2004). The urban OKCNET stations fall into UCZ 153 classifications of UCZ1 and UCZ2 (intensely developed urban); the suburban OKCNET stations 154 fall into UCZ classifications of UCZ4 through UCZ7 (highly developed, medium, or low density 155 156 urban, suburban to semi-rural); the rural OKCNET stations fall into UCZ classifications of UCZ7 (semi-rural) (Basara et al. 2010; Basara et al. 2011). 157

The Oklahoma Mesonet is a rural network of 120 meteorological stations with minimal influences from urban landscapes (McPherson et al. 2007; Basara et al. 2008). Each of the Mesonet stations is located within a fenced 100 m² plot of land and measures more than 20 environmental variables, including wind at 2 and 10 m, air temperature at 1.5 and 9 m AGL, and short wave radiation, that are used in the analysis of this study. The average temperature at 9 m

AGL at the seven Mesonet sites surrounding the OKC metropolitan area (i.e., El Reno (ELRE), 163 Guthrie (GUTH), Kingfisher (KIN2), Minco (MINC), Norman (NRMN), Washington (WASH), 164 and Spencer (SPEN); see Fig. 1) are calculated as background rural temperature following the 165 approach of Basara et al. (2008) and Klein (2012). The UHI intensity at each OKCNET site is 166 167 defined as the difference between the temperature at the OKCNET site and the background rural 168 temperature. Note that the average elevation difference between the OKCNET sites (≈370 m above sea level) and the seven rural Mesonet sites (≈ 363 m above sea level) is approximately 7 169 m. Using mean temperature at the seven Mesonet sites as background rural temperature provides 170 a more robust measure of UHI intensity and minimizes the inherent variability between rural 171 sites that can impact the magnitude of UHI values (Hawkins et al. 2004; Sakakibara and Owa 172 173 2005; Hunt et al. 2007; Lee and Baik 2010; Mohsin and Gough 2012). For example, as a result 174 of the urbanization in recent years, the NRMN station was at the edge of an urban area according to the U.S. Geological Survey (USGS) 2006 National Land Cover Data (NLCD; Fig. 1), where 175 176 the measured rural temperature may be biased high. On the other hand, the ELRE site to the west of the metropolitan area is known to experience more rapid nighttime cooling than other nearby 177 178 Mesonet sites and often has a low bias (Hunt et al. 2007).

179 Richardson number (*Ri*), an indicator of dynamic stability of an air layer, considers 180 effects of both wind shear and buoyancy on the atmospheric stability. To investigate the diurnal 181 cycle of near-surface atmospheric stability and its impact on UHI development, the *Ri* at 182 Mesonet sites around OKC was estimated using (Bodine et al. 2009)

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$$Ri = \frac{g[(T_{9m} - T_{1.5m})/\Delta z_T + \Gamma_d]\Delta z_u^2}{T_{1.5m}[u_{10m} - u_{2m}]^2},$$
 (1)

184 where g is the acceleration due to gravity, $\Gamma_d = 0.01^{\circ}$ C m⁻¹ is the dry adiabatic lapse rate, 185 T_{9m} and $T_{1.5m}$ are the air temperatures measured at 9 and 1.5 m AGL, and u_{2m} and u_{10m} are 186 wind speed at 2 and 10 m AGL, respectively. The height differences between the measurement 187 levels are $\Delta z_T = 7.5$ m for air temperature and $\Delta z_u = 8.0$ m for wind speed.

188 One of the surrounding Mesonet sites, KIN2, was deployed in March 2009. A few OKCNET sites were decommissioned in November 2010, i.e., reliable temperature data over the 189 190 urban area were no longer available from thereon. Thus the investigation of urban effects focuses on the period of April 2009 - October 2010 in this study. Precipitation has been reported 191 192 to reduce the difference in the heating/cooling rate between the urban and rural areas, thus suppressing UHI development (Chow and Roth 2006; Lee and Baik 2010). Time periods with 193 precipitation at any OKCNET sites or the seven surrounding Mesonet sites were not considered 194 in this study to avoid the impact of precipitation on UHI. Since the spatial distribution of UHII 195 196 is to be examined, all the sites need to have the same measurement period. So only the time periods when data from all the sites were available between April 2009 and October 2010 (total 197 6937 hours) were considered when investigating urban-rural differences. On the other hand, the 198 199 Oklahoma Mesonet has been continuously operational. The temperature inversion between 1.5 and 9 m AGL at the seven Mesonet sites surrounding OKC were examined for a longer period 200 (i.e., April 2009-December 2012) to diagnose possible seasonal variations of UHI intensity. 201

In addition to values at spatially distributed observation sites, spatial patterns of UHII and wind speed were analyzed using the Kriging interpolation method. The Kriging method is popular in mapping meteorological and chemical variables based on station observation data in diverse applications (e.g., Chen et al. 2014; Smoliak et al. 2015; Zou et al. 2015). The Kriging function embedded in the Interactive Data Language (IDL, Version 8.4) was used in this study asin Chen et al. (2014).

208 **3. Results**

3.1 Mean spatial distributions and diurnal variations of UHI and wind speed

210 **3.1.1 UHI intensity and relationship with spatial distributions of wind speed**

The spatial distributions of UHII and wind speed are overlaid on top of land use categories in Fig. 2. The strongest UHI intensity was mostly confined around the central business district (CBD) during both daytime and nighttime except for a hotspot of KNW103 during nighttime (Fig. 2b). The spatial maps of UHI intensity produced by the Kriging method illustrate elongated heat plumes north of the CBD during both daytime and nighttime (Fig. 3a, b), which can be explained by downwind transport of heat by the predominant southerly winds.

While urban effects on temperature are quite widely discussed in the literature, less 217 218 information is available about urban effects on wind patterns (Klein 2012; Klein and Galvez 219 2014). Spatial patterns of mean wind speed around OKC were examined using the OKCNET 220 observations (Fig. 2c,d). The corresponding analysis based on the Kriging method are also shown in Fig. 3c,d. Unlike the elongated feature of UHI intensity, wind speeds showed a more 221 concentric pattern around the CBD. Wind speed was slowest during both daytime and nighttime 222 223 around the CBD, where the UHI intensity was the strongest. Having the largest wind speed reduction centered around the CBD suggests a strong impact of surface roughness which is 224 largest in this area. Roughness also affects the aerodynamic resistance of sensible heat transfer. 225 226 Larger/smaller roughness leads to stronger/weaker vertical mixing and more/less efficiency to transfer sensible heat from the land surface to the atmospheric boundary layer (ABL) (Lee et al. 227 228 2011).

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229 In the humid southeast and south central United States (including Oklahoma), the rural 230 land is densely vegetated, owing to ample precipitation, and is aerodynamically rough. Zhao et al. (2014) argue that in this humid region, sensible heat transfer from the surface to the ABL is 231 232 more efficient in rural than in urban areas, leading to relatively lower/higher surface temperatures in rural/urban area. Such a process is attributed in Zhao et al. (2014) to largely 233 explain MODIS-derived daytime land surface UHII in this region, which is termed as the 234 roughness warming theory. The roughness warming theory was derived when comparing the 235 aerodynamic resistance/roughness between rural land-use categories and a single urban category 236 237 (i.e., the intra-urban variation of roughness is ignored). Given the intra-urban variation of roughness due to different building densities and heights, according to the roughness warming 238 theory aerodynamically smoother urban areas should experience stronger daytime UHII than 239 240 aerodynamically rougher urban areas (e.g., CBD), assuming that the ratio of roughness length of momentum to heat remains roughly constant across the entire urban area (Moriwaki and Kanda 241 2006; Kato et al. 2008; Sugawara and Narita 2009; De Ridder et al. 2012). However, this is not 242 the case for OKC. On the contrary, the aerodynamically roughest CBD area experienced the 243 highest UHII (Figs. 2a,b, 3a,b). Thus, the roughness warming theory of Zhao et al. (2014) used 244 245 for explaining the land surface UHI may not explain the air temperature UHI observed in this study. Other intrinsic causative factors, e.g., thermal properties of urban surfaces (Grimmond 246 and Oke 1999; Ogoli 2003; Liu et al. 2006; Zhu et al. 2009; Bohnenstengel et al. 2011; Yang et 247 248 al. 2013), anthropogenic heat (Ichinose et al. 1999; Fan and Sailor 2005; Grossman-Clarke et al. 2005; Schlunzen et al. 2010), reduction in evaporative cooling due to impervious surfaces (Taha 249 250 1997), and trapping of longwave radiation by urban buildings (Arnfield 2003), must have played

more important roles in contributing to the air temperature UHII in OKC, as suggested in a
modeling study conducted by Ryu and Baik (2012).

253 Detailed diurnal variation of UHI is still subject to debate (Memon et al. 2009; Imhoff et 254 al. 2010; Hu et al. 2013c; Zhao et al. 2014). A better understanding of UHIIs' temporal variation 255 could help to diagnose its causative factors (Hu et al. 2013c). Mean diurnal variation of UHII 256 between April 2009 and October 2010 at OKCNET sites was calculated after removing the 257 periods when precipitation occurred or data from certain sites were missing. All the sites show a 258 prominent diurnal variation of UHII with higher values during nighttime (Fig. 4a,b). The UHII 259 normally increased rapidly around the early evening transition (EET), i.e., 7-8 PM (1900-2000 260 LST), and then stayed at a roughly constant level throughout the night until early next morning when the convective boundary layer developed. Note that since the sunset and sunrise time 261 262 varies, the transition time in the diurnal variation of UHII are different in different seasons. Such an issue will be discussed in section 3.2. The characteristics of diurnal variation of UHII shown 263 in Fig. 4a are consistent with existing studies for a few other cities, such as Bucharest (Tumanov 264 et al. 1999), Paris (Lemonsu and Masson 2002), New York City (Gedzelman et al. 2003), 265 Orlando (Yow and Carbone 2006), London (Bohnenstengel et al. 2011; Chemel and Sokhi 2012; 266 267 Barlow et al. 2015), Thessaloniki and Athens (Giannaros and Melas 2012; Giannaros et al. 2013). In all of these studies, UHI intensity was quantified using near surface air temperature. 268 Reversed diurnal variation of UHII (i.e., higher UHII during daytime than nighttime) was 269 270 reported when it was quantified using remotely-sensed land-surface temperature (Imhoff et al. 2010; Peng et al. 2012; Zhao et al. 2014). As discussed in the introduction, remotely sensed 271 land-surface temperatures and UHIIs must be carefully interpreted and do not necessarily 272 273 characterize well urban temperatures. Another advantage of quantifying UHII using near-surface

air temperature is that ambient air temperature is directly related to public health (Basara et al.
2010; Tan et al. 2010; Oswald et al. 2012). Future studies to further investigate the two different
quantifications of UHII (i.e., using air temperature and land surface temperature) and combine
their advantages are greatly needed (Schwarz et al. 2012).

The rapid increase of UHII around the EET is likely related to rapid changes of mean 278 279 flow and turbulence in the ABL. Around sunset, with the rapid decline of solar radiation and 280 sustained radiational cooling of the surface, upward sensible heat fluxes decreased and convective eddies subsided quickly. Consequently, near-surface atmospheric stability increased 281 282 quickly as indicated by the rapid increase of mean Ri at the Mesonet sites around OKC (Fig. 5). At 7 PM (1900 LST), the mean Ri became larger than 0.2, which is considered a quite stable 283 284 condition (Banta et al. 2003; Galperin et al. 2007). Turbulent kinetic energy (TKE) in the upper part of the ABL decays quickly during the EET and this part of the ABL becomes the residual 285 layer, which often becomes decoupled from the newly formed stable layer near the surface 286 (Acevedo and Fitzjarrald 2001; Acevedo et al. 2012; Bonin et al. 2013; Rizza et al. 2013; Klein 287 et al. 2014). Rapid reduction of near-surface wind speed around 1800 LST (Fig. 6) is an 288 indication of decoupling of the near-surface stable boundary layer from the upper layers with 289 290 larger horizontal momentum. Impacts of surface heterogeneities (urban vs. rural) are enhanced in the shallow near-surface stable boundary layer (Godowitch et al. 1987; Acevedo and 291 Fitzjarrald 2001). Rural near-surface temperature drops quickly in the shallow stable boundary 292 293 layer due to radiational cooling of the surface. In contrast, the longwave radiative heat loss at street level in urban areas is reduced due to multiple reflections among urban buildings (Oke 294 295 1981). Meanwhile, heat stored in the urban materials during the day begins to release during the 296 EET (Ogoli 2003; Harman and Belcher 2006; Liu et al. 2006; Zhu et al. 2009; Bohnenstengel et 297 al. 2011; Zajic et al. 2011; Yang et al. 2013). Together with anthropogenic heat, this extra heat 298 in the urban region is released into and confined in the urban boundary layer (Ichinose et al. 1999; Fan and Sailor 2005; Grossman-Clarke et al. 2005; Rizwan et al. 2008; Schlunzen et al. 299 300 2010; Kotthaus and Grimmond 2014a, 2014b; Barlow et al. 2015). Consequently, urban nearsurface temperatures decrease slowly in a more neutral urban boundary layer induced by the 301 stronger turbulent vertical mixing due to higher heat emissions and rougher surface in cities 302 (Clarke 1969; Oke 1987; Uno et al. 1988; Martilli et al. 2002; Nelson et al. 2011; Salamanca et 303 al. 2014; Bohnenstengel et al. 2015). As a result of different cooling rates at rural and urban 304 305 sites for 2-3 hours, UHII increased quickly during the EET and stayed at a roughly constant level 306 for the rest of the night (Fig. 4a,b).

Previous studies suggested that spatial variability of temperature in rural areas played a 307 very important role in determining the UHII (Hawkins et al. 2004). A question arises as to how 308 important the EET cooling rate in rural areas is for UHI development (Yow and Carbone 2006). 309 The relationship between rural background temperature change rate during the EET (2 hours 310 311 before sunset) and that of UHI intensity immediately after the EET (2 hours after sunset) are thus further examined (Fig. 7). The mean UHI intensity at the OKCNET "urban" sites (i.e., KCB101-312 313 109, Basara et al., 2010) is chosen for analysis. Different sunset time during different month is accounted for. The statistic investigation based on 2009-2010 data demonstrates that the near-314 surface cooling rate in the rural area around OKC during the EET shows a significant correlation 315 316 with the UHI intensity at early evening with a correlation coefficient of -0.63 (Fig. 7). The mean UHI intensity at early evening roughly represents the mean nighttime UHI intensity (Fig. 4a). 317 318 Thus, the near-surface cooling rate in the rural area during the EET is confirmed to play a critical role in determining the nocturnal UHI intensity with strong/weak EET cooling rate likely leadingto strong/weak nocturnal UHI.

Similar to the cooling rate during the EET, the heating rate during the morning transition 321 322 was also larger in the rural than urban area (Figure not shown), which is consistent with previous studies (Oke 1987). The average absolute values of temperature change rate during the early 323 evening and morning transition are shown in Fig. 8. The temperature change rate shows a 324 concentric distribution with the lowest rate located over OKC's CBD, and increases from urban 325 to rural zones (Fig. 8), indicating the moderating effects of urban to diurnal temperature change. 326 327 The temperature change rate during the evening and morning transition may provide an alternate way to estimate the magnitude of urban footprints. 328

As discussed above, UHI intensity exhibited a large spatial variation over OKC (Figs. 2, 329 330 3, 4). UHI intensity over OKCNET sites varied between 0.4 and 2.1 °C during nighttime, while it varied between -0.2 and 1.0 °C during daytime (Fig. 4a). The large spatial variation of UHI 331 intensity over OKC may be primarily caused by the different surface structures and cover at each 332 site, as also reported for other cities (e.g., Shahgedanova et al. 1997; Eliasson and Svensson 333 334 2003; Alcoforado and Andrade 2006; Kolokotroni and Giridharan 2008; Bohnenstengel et al. 335 2011; Brandsma and Wolters 2012; Oswald et al. 2012; Suomi and Kayhko 2012; van Hove et al. 2015). Classifying all the sites in cities with different surface structure and cover into a single 336 urban category may be inadequate to accurately quantify UHI in terms of its intensity and 337 338 variation (Stewart 2011; Stewart and Oke 2012). According to the three-category (i.e., urban, suburban, and rural) classification of Basara et al. (2010), most of the sites starting with KCB 339 (except KCB110) are located in the CBD and their surface type is classified as "urban". These 340 341 "urban" sites experienced higher UHI intensities than most of the remaining OKCNET sites

342 during both daytime and nighttime (Figs. 2, 3, 4). Four OKCNET sites (i.e., KSW101, KSW110, KSE102, KNE103) are classified as "rural" surface type in Basara et al. (2010) and these sites 343 experienced lower UHI intensities than most of the other OKCNET sites (Figs. 2, 3, 4). The 344 large spatial variation of UHI intensity across OKC suggests that determining UHI intensity 345 using the temperature difference between a certain urban site and a certain rural site may lack 346 objective meaning and climatological relevance. These results thus justify the proposal by a few 347 recent studies (e.g., Basara et al. 2010) of classifying measurement sites into detailed (to certain 348 degrees) urban categories for objective UHI quantification and description. 349

The Basara et al. (2010) 3-category classification is further compared with the more detailed classification of seven different UCZs defined by Oke (2004). The UHII diurnal variation show a large variability within individual UCZs (Fig 4b), while the 3-category classification better captures the differences in the UHII characteristics among the OKCNET sites. We have thus decided to use the classification into rural, suburban, and urban sites as proposed by Basara (2010) in this study.

356 **3.1.2** Wind speed and implications for treatments in numerical models

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Due to diurnal variation of vertical coupling strength (strong coupling in daytime and 358 359 weaker coupling at nighttime), the diurnal cycle of surface wind was prominent, exhibiting a 360 maximum/minimum in the daytime/nighttime (Fig. 6). During the daytime, stronger downward transport of boundary layer momentum led to stronger surface winds compared to nighttime. 361 Wind speeds at each individual site were largely determined by the roughness of each site 362 (Kamal et al. 2015) and wind climatology in its surrounding environment. Two OKCNET sites 363 on the west side of OKC, KNW104 (suburban) and KSW101 (rural) with relatively low 364 roughness being located on dispersed settlement and grassland (Basara et al. 2011), experienced 365

strong wind speeds (Figs. 2c,d, 9). The climatological east-to-west gradient of wind speed in
presence of dominant southerly wind in Oklahoma (Song et al. 2005) is another factor to explain
the large wind speeds at these sites. Such an east-to-west gradient of southerly wind speed in
Oklahoma was previously noticed in both observation and modelling results (Hu et al. 2013a; Hu
et al. 2013c).

371 Urbanization can have two different effects on surface wind: (i) enhanced surface roughness reduces surface wind speeds (Kamal et al. 2015), while (ii) stronger downward 372 momentum transport due to enhanced vertical mixing increases surface speeds (Wang et al. 373 374 2007b; Hu et al. 2013c). Wind speeds at OKCNET sites (except KNW104 and KSW101) were always smaller than at the surrounding rural Mesonet sites (Fig. 9), which suggests that the 375 effects of the enhanced urban surface roughness were dominant. The urban effect on wind in 376 377 terms of the magnitude of wind speed reduction was more prominent during daytime than during nighttime. The reductions of near-surface wind speed in the CBD area are as large as 3.5 m s⁻¹ 378 during daytime while the magnitude of wind speed reduction decreases to 2 m s⁻¹ during 379 nighttime (Fig. 9). 380

Figures 2, 3, and 9 imply that the near-surface wind speed in urban areas is typically 381 382 weaker than over the surrounding rural areas due to the dominant effects of enhanced roughness in urban. However, in three-dimensional simulations with the Weather Research and Forecasting 383 (WRF) model, higher values of near-surface wind speed are at times simulated over urban than 384 over rural areas (e.g., during the early evening transition, see Supplement Fig. A1). These results 385 which are likely unrealistic according the wind speed data observed at the OKCNET sites, 386 suggest that the vertical transport of momentum in mesoscale models may be over-estimated. 387 The advancement of model capability to handle vertical transport of momentum has been slower 388

compared to the advancement of model capability to handle transport of scalars due to the fact
that most previous research efforts in terms of vertical transport had been focused on scalars
rather than momentum (Frech and Mahrt 1995; Storm et al. 2009; Hu et al. 2013a; Ngan et al.
2013; Draxl et al. 2014; Gutiérrez et al. 2015).

393 **3.2 Seasonal variation of UHI**

Seasonal variation of UHI intensity in OKC during April 2009-October 2010 (Fig. 10a) 394 395 did not show a clear warm-cold season contrast as reported in other cities (e.g., Magee et al. 1999; Steinecke 1999; Montavez et al. 2000; Jonsson 2004; Kim and Baik 2005; Hinkel and 396 Nelson 2007; Zhou and Shepherd 2010; Memon et al. 2011; Yang et al. 2013). Hu et al. (2013c) 397 398 concluded that rural temperature inversion strength can serve as an indicator of nocturnal UHI intensity based on the analysis of temperature data in July 2003 and model simulation results. 399 400 Thus, temperature inversion strength (defined as temperature difference between 1.5 and 9 m AGL) at the seven surrounding Mesonet sites is also examined (Fig. 10b). The temperature 401 402 inversion strength had a similar variation as that of UHII and did not show a clear warm-cold season contrast. Monthly variation of percentiles (median, 25/75%, and 5/95%) of daily mean 403 nocturnal UHII was also similar as those of nocturnal rural inversion strength (Fig. 11), even 404 though the monthly percentiles may not be statistically significant in certain months due to many 405 406 missing values because of precipitations (See Fig. 10). The UHII and surrounding rural inversion strength had a significant correlation during nighttime (2200 - 0500 CST) with a 407 correlation coefficient of 0.79 (Fig. 12a). As discussed above, urban effects including reduced 408 409 outgoing longwave radiation, extra heat, and stronger roughness lead to a more neutral and relatively thicker urban boundary layer and slower temperature decrease in contrast to rapid 410 411 temperature decrease in the shallow stable rural boundary layer during the EET. Stronger rural

412 temperature inversion is normally associated with a shallower and more stable boundary layer 413 and allows urban effects to manifest more prominently with higher UHI intensity (Hu et al. 2013c), effectively explaining the positive correlation between rural inversion strength and UHI 414 intensity. Two exceptional points (i.e., 29 March 2010 and 29 October 2010) stand out in Fig. 415 12a. Two reasons were responsible for these exceptions: first, extremely strong inversion (~8 °C 416 between 1.5 and 9 m AGL) occurred at the El Reno (ELRE) Mesonet site on these nights. 417 Similar significant nocturnal inversion at ELRE site in presence of clam winds, low humidity, 418 and clear skies was previously noticed and reported by Hunt et al. (2007); second, nocturnal 419 420 warming events occurred at the Minco (MINC) Mesonet site. Various nocturnal warming events 421 may occur at certain rural stations due to a few reasons (White 2009; Nallapareddy et al. 2011; Hu et al. 2013b; Hu and Xue 2015), including cold front passages. Detailed investigation of the 422 rural nocturnal warming events is beyond the scope of this study. 423

424 Given the significant correlation between rural inversion strength and nocturnal UHII, further investigation of a longer term of rural inversion strength can help diagnose the seasonal 425 variation of nocturnal UHI intensity. Thus, longer term Mesonet data (April 2009-December 426 2012) are examined. Monthly variation of median, 25/75%, and 5/95% percentiles of daily mean 427 nocturnal rural inversion strength around OKC during this longer period is shown in Fig. 13. 428 429 The years 2011 and 2012 were exceptionally dry (Ramsey et al. 2014). There were only few precipitation events during these years, thus more inversion data are counted for and the statistics 430 431 are more reliable than Fig. 11b. The maximum median nocturnal inversion occurred in October. The standard deviations of rural inversion were smaller and the extreme values (indicated by 432 95% percentile) of rural inversion were lower in June and July (Fig. 13). Given the relationship 433

between rural inversion and UHI intensity discussed above, the strongest nocturnal UHI was lesslikely to occur in June and July.

436 Wind speed has been reported to modulate UHI intensity in various cities (Morris et al. 437 2001; Unger et al. 2001; Fast et al. 2005; Steeneveld et al. 2011). The correlation between rural wind speed and nocturnal UHI intensity during April 2009-October 2010 was examined. 438 439 Nocturnal UHI intensity normally decreased with increased wind speed with a correlation 440 coefficient of -0.72 (Fig. 12b). Larger wind speed leads to stronger turbulence and stronger mechanical vertical mixing, which reduce or eliminate rural background nocturnal temperature 441 442 inversion. Since rural temperature inversion is a good indicator of nocturnal UHI intensity as discussed above, larger wind speeds decrease UHI intensity. Other processes (e.g., clouds) also 443 play roles in modulating UHI intensity (Morris et al. 2001; Rosenzweig et al. 2005; Yow and 444 Carbone 2006; Hoffmann et al. 2012), which can partially explain the scattering of the data 445 points in Fig. 12b. Unfortunately, cloud data are not available from OKCNET and Mesonet 446 sites. 447

Even though a clear warm-cold season contrast in the magnitude of UHII in OKC was 448 not discerned during April 2009-October 2010 (Fig. 10a), seasonal variation of the timing of 449 450 UHI was prominent (Fig. 14). Figure 14 shows the mean UHII at OKCNET sites as a function of month and time of the day. Note comparison of UHI intensity between different months in 451 Fig. 14 is not meaningful since the number of available data during each month is different (see 452 the data availability in Fig. 10a after removing periods with precipitation and missing data at 453 certain sites). Figure 14 further confirms the prominent diurnal variation of UHI intensity, i.e., 454 nocturnal UHI was strong while daytime UHI was weak. The timing of onset/subsiding of 455 nocturnal UHI showed a clear monthly variation. The time span of nocturnal UHI was short 456

during warm months, while it was relatively longer during cold months. The onset timing of
nocturnal UHI roughly followed the sunset time. This further confirms the critical roles played
by the physical processes during the EET in the development of UHI.

460

4. Conclusions and discussion

Using the data recorded from a dense surface observing network, i.e., the Oklahoma City 461 micronet, during April 2009-October 2010, observed spatial distribution of UHII over Oklahoma 462 463 City (OKC) is investigated. UHII exhibited a large spatial variation over OKC. The widelyvaried UHII over OKC is partially explained by the different surface structure and cover at each 464 465 site. The large variation of UHII across the urban area suggests that determining UHII using the temperature difference between an individual urban-rural site pair may lack objective meaning. 466 467 It is better to classify measurement sites into detailed categories for objective UHI quantification 468 and description as suggested by recent studies (e.g., Basara et al. 2010).

During both daytime and nighttime, the strongest UHII was mostly confined around the central business district (CBD) where surface roughness is the highest in the OKC metropolitan area. These results do not corroborate the roughness warming theory of Zhao et al. (2014), according to which, aerodynamically smoother urban areas would experience stronger daytime UHII than aerodynamically rougher urban areas (e.g., CBD).

UHII of OKC increased prominently around the early evening transition (EET) and stayed at a fairly constant level through the night. The boundary-layer processes during the EET played a critical role in determining the nocturnal UHII in the absence of disturbances such as precipitation. Associated with rapid decline of solar radiation during the EET, a stable boundary layer develops close to the ground. Rural temperatures in the shallow stable boundary layer decrease quickly due to radiative cooling. Meanwhile, heat stored in the urban building 480 materials during the day released rapidly, together with the anthropogenic heat emissions, heated 481 the urban boundary layer. This extra heat, together with reduced outgoing longwave radiation (due to wall reflection etc.) and elevated roughness, led to a more neutral urban boundary layer, 482 483 in which temperature near the surface decreased slower than in the rural stable boundary layer. As a result of different cooling rates between urban and rural, UHII increased rapidly during the 484 485 EET. The near-surface cooling rate in the rural area during the EET regulated the nocturnal UHII with a correlation coefficient of -0.63. Factors such as wind speed and clouds may have 486 affected the stability/depth of background nocturnal boundary layer, thus modulating UHII. 487

488 Nocturnal rural temperature inversion strength had a similar day-to-day variation as that of UHII. The nocturnal UHII and surrounding rural inversion strength are significantly 489 correlated with a correlation coefficient of 0.79. A stronger rural inversion normally means a 490 shallower surface layer and a larger EET temperature decrease in rural area compared to the 491 urban area, which leads to a stronger UHII. The rural inversion strength did not show a clear 492 warm-cold season contrast during April 2009-October 2010. Thus warm-cold season contrast of 493 494 UHII in OKC was not prominent during this period. Analysis of a longer term (April 2009-December 2012) of rural inversion strength suggested that the strongest nocturnal UHI in OKC 495 496 was more likely to occur in months other than June and July. Seasonal variation of the timing of UHI was prominent with shorter/longer time span of nocturnal UHI during warm/cold months, 497 which is directly linked to the sunset and sunrise timings. 498

Though not shown here, surface ozone (O_3) was removed during the EET due to deposition and chemical reactions in the stable boundary layer. Shallower the stable boundary layer normally led to a quicker surface O_3 reduction. The O_3 removal rate during the EET showed a good correlation with the rural cooling rate. Thus, the characteristics of certain chemical species such as O₃ during the EET can be used together with the rural cooling rates as
indications of UHI development. The ambient concentration of other pollutants can be also
indicative of the nocturnal UHII (Lai and Cheng 2009).

506

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513

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923 Figure captions:

Figure 1. (a) Location of the OKCNET stations (red dots) and seven surrounding Oklahoma 924 Mesonet sites (i.e., ELRE, GUTH, KIN2, MINC, NRMN, WASH, and SPEN in blue dots). The 925 central business district (CBD) of OKC is also marked. The background shade corresponds to the 926 land use categories derived from the U.S. Geological Survey (USGS) 2006 National Land Cover 927 Data (NLCD) at a spatial resolution of 30 meters, in which the urban land use was divided into 928 929 three categories: low-intensity residential (category 31), high-intensity residential (32), and commercial/industrial (33). In the CBD, symbols overlap due to the high spatial density of the 930 OKCNET stations. (b) Spatial distribution of built-up area fraction also derived from the NLCD. 931

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Figure 2. Spatial distribution of (a, b) mean UHII (defined as the difference between temperature at each OKCNET site and rural background temperature computed as average temperature at the seven Mesonet sites) and (c, d) wind speed during (top) daytime (i.e., 0900-1700 CST) and (bottom) nighttime (i.e., 2200-0500 CST) in April 2009-October 2010. The background shade shows again the land use categories derived from the 2006 National Land Cover Data (NLCD). In the CBD, not all station names are shown.

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Figure 3. Spatial patterns of (a, b) mean UHII and (c, d) wind speed computed with a kriging interpolation method (using the data shown in Fig. 2) during (top) daytime and (bottom) nighttime in April 2009-October 2010. As reference, the location of some of the sites is indicated by the station names.

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Figure 4. a) Mean diurnal variation of UHII at each OKCNET site during April 2009-October 2010. The OKCNET sites are classified into three categories (i.e., urban, suburban, and rural) with different colors based on the neighborhood land cover characteristics surveyed in Basara et al. (2010). b) Similar as a), but the OKCNET sites are classified into different urban climate zones (UCZs) defined by Oke (2004).

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Figure 5. Mean diurnal variation of Richardson number (Ri) and short wave radiation at 10
mesonet sites around OKC (i.e., OKCE, OKCN, OKCW, MINC, SPEN, ELRE, GUTH, KIN2,
NRMN, and WASH) during April 2009-October 2010.

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Figure 6. Mean diurnal variation of wind speed (WSPD) at OKCNET sites during April 2009-October 2010.

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- Figure 7. Correlation between rural cooling rate during the early evening transition (EET, i.e., 2
- hours before sunset) and average UHII at early evening (2 hours after sunset) at OKCNET urban
- sites during April 2009-October 2010.

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Figure 8. Spatial distribution of average temperature change rate during the early evening and morning transition based on (a) spatially distributed observations and (b) Kriging analysis.

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Figure 9. Mean diurnal variation of wind speed difference between OKCNET sites and the sevensurrounding mesonet sites during April 2009-October 2010.

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Figure 10. Time series of (a) UHII at OKCNET urban sites and (b) rural average temperature inversion at the seven surrounding mesonet sites during April 2009-October 2010.

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Figure 11. Monthly variation of median, 25/75%, and 5/95% percentiles of mean nocturnal
(2200-0500 CST) (a) UHII and (b) rural inversion strength around OKC during April 2009October 2010.

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Figure 12. Correlations between daily nocturnal (2200-0500 CST) UHII at the OKCNET urban sites and (a) rural inversion strength, and (b) rural wind speed during April 2009-October 2010.

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Figure 13. Monthly variation of median, 25/75%, and 5/95% percentiles of mean nocturnal (2200-0500 CST) rural inversion strength around OKC during April 2009-December 2012.

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Figure 14. Mean UHII over the OKCNET sites as a function of month and time of the day.



Figure 1. (a) Location of the OKCNET stations (red dots) and seven surrounding Oklahoma Mesonet sites (i.e., ELRE, GUTH, KIN2, MINC, NRMN, WASH, and SPEN in blue dots). The central business district (CBD) of OKC is also marked. The background shade corresponds to the land use categories derived from the U.S. Geological Survey (USGS) 2006 National Land Cover Data (NLCD) at a spatial resolution of 30 meters, in which the urban land use was divided into three categories: low-intensity residential (category 31), high-intensity residential (32), and commercial/industrial (33). In the CBD, symbols overlap due to the high spatial density of the OKCNET stations. (b) Spatial distribution of built-up area fraction also derived from the NLCD.



Figure 2. Spatial distribution of (a, b) mean UHII (defined as the difference between temperature at each OKCNET site and rural background temperature computed as average temperature at the seven Mesonet sites) and (c, d) wind speed during (top) daytime (i.e., 0900-1700 CST) and (bottom) nighttime (i.e., 2200-0500 CST) in April 2009-October 2010. The background shade shows again the land use categories derived from the 2006 National Land Cover Data (NLCD). In the CBD, not all station names are shown.



Figure 3. Spatial patterns of (a, b) mean UHII and (c, d) wind speed computed with a kriging interpolation method (using the data shown in Fig. 2) during (top) daytime and (bottom) nighttime in April 2009-October 2010. As reference, the location of some of the sites is indicated by the station names.



Figure 4. a) Mean diurnal variation of UHII at each OKCNET site during April 2009-October 2010. The OKCNET sites are classified into three categories (i.e., urban, suburban, and rural) with different colors based

on the neighborhood land cover characteristics surveyed in Basara et al. (2010). b) Similar as a), but the OKCNET sites are classified into different urban climate zones (UCZs) defined by Oke (2004).





Figure 5. Mean diurnal variation of Richardson number (*Ri*) and short wave radiation at 10 mesonet sites around OKC (i.e., OKCE, OKCN, OKCW, MINC, SPEN, ELRE, GUTH, KIN2, NRMN, and WASH) during April 2009-October 2010.



Figure 6. Mean diurnal variation of wind speed (WSPD) at OKCNET sites during April 2009-October 2010.



Figure 7. Correlation between rural cooling rate during the early evening transition (EET, i.e., 2 hours before sunset) and average UHII at early evening (2 hours after sunset) at OKCNET urban sites during April 2009-October 2010.



Figure 8. Spatial distribution of average temperature change rate during the early evening and morning transition based on (a) spatially distributed observations and (b) Kriging analysis.



Figure 9. Mean diurnal variation of wind speed difference between OKCNET sites and the seven surrounding mesonet sites during April 2009-October 2010.



Figure 10. Time series of (a) UHII at OKCNET urban sites and (b) rural average temperature inversion at the seven surrounding mesonet sites during April 2009-October 2010.



Figure 11. Monthly variation of median, 25/75%, and 5/95% percentiles of mean nocturnal (2200-0500 CST) (a) UHII and (b) rural inversion strength around OKC during April 2009-October 2010.



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