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Study on the Urban Heat Island Effects and Its Relationship with Surface Biophysical Characteristics Using MODIS Imageries

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Abstract This study assesses surface urban heat island (UHI) and its associated surface physical characteristics using remote sensing approaches. TERRA/MODIS images acquired in 2005 in three different seasons were selected to generate land surface temperature and surface characteristics for the Changsha-Zhuzhou-Xiangtan metropolitan area in China. The intensity of urban heat island effects and its seasonal variations were examined. The result showed that UHI effects were significant both in the summer and the spring. Land surface temperatures in the city were 8℃ to 10℃ warmer than those in surrounding rural areas in the spring and the summer seasons. Although UHI effects exist in winter, they are not significant. Land surface temperature in the city was 4℃ warmer than that in surrounding rural areas in winter. This study uses normalized difference vegetation index (NDVI) and normalized difference built-up index (NDBI) as indicators of surface physical characteristics and investigates the relationship among land surface temperature (LST), NDVI and NDBI. The results from this study indicate that, while the relationship between LST and NDVI changes in different seasons, there is a strong positive linear relationship between NDBI and LST for all seasons. The amount of slope and intercept of the linear relationship between NDBI and LST can indicate the magnitude of UHI for different seasons. This finding suggests that NDBI provides an alternative physical indicator for analyzing LST quantitatively over different seasons, and therefore providing a useful way to study UHI effects using remote sensing.

Keywords urban heat island; biophysical indicators; MODIS image; Changsha-Zhuzhou-Xiangtan area; China

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Introduction

In urbanizing areas, the rapid urbanization and accelerated urban sprawl have led to the conversion of the natural landscape into a largely impervious landscape. Human induced changes of the natural ecosystem have dramatically changed radiative, thermal, moisture, roughness and emission properties of the earth's surface and the atmosphere above[1-3]. These urban surface modifications resulted in increased local atmospheric and surface temperatures in urban areas compared to the surrounding rural areas[4]. As cities grow in both population and physical size due to urbanization, the urban-rural difference in atmospheric and surface temperature also increased, which have significant effects on urban climate, environmental change and the quality of human life[1, 3]. As a

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result, the UHI research has been the major concern of many urban climate studies.

Although urbanization accelerated the pace of achieving economic prosperity in China since the 1980s, rapid urban transitions have significantly affected the lives of urban inhabitants as well as worsen the urban environment and urban climate[3, 5]. Therefore, to better understand the effects of urbanization on the environment and climate, it is essential to study UHI in rapidly developing cities in China.

Different approaches have been used to analyze UHI characteristics[4, 6, 7]. The remote sensing based approaches have great potential to reveal thermal characteristics in urban areas and have been extensively used for UHI studies at various spatial scales [7-10]. Because of recent developments in remote sensing technologies in recent years, the Moderate Resolution Imaging Spectroradiometer (MODIS) data with 36 spectral bands have become readily available and can be used to extract both surface thermal features and biophysical descriptors, which could be used to detect the spatial extent and magnitude of UHI and provide the possibility of examining the relationship between land surface temperatures (LST) and biophysical descriptors. However, the potential of achieving better results from MODIS data for UHI studies and related studies of climate change and urban ecosystems has yet to be confirmed.

Many studies frequently employed thematic land use and land cover data and analyzed simple correlation between LULC types and their thermal signatures. However, land surface temperature variation associated with land surface biophysical characteristics is not fully understood. Alternatively, some researches[11, 12] have proved that land surface temperature has a correlation with normalized difference vegetation index (NDVI) derived from remotely sensed data. The negative correlation between land surface temperature (LST) and NDVI is found in urban areas. Therefore, NDVI is suggested as an indicator of surface urban heat island. However, NDVI is subject to seasonal variations and has a nonlinear relationship with LST. Therefore, NDVI alone may not be a sufficient indicator to study UHI effect quantitatively. Urbanization transforms the natural landscape into anthropogenic impervious surfaces which are land covers with buildings, roads, parking lots, and other paved surfaces. The amount of impervious surfaces is an important indicator of urban environmental quality[13]. Analyzing the relationship between LST and impervious surface area in an urbanized environment would provide an alternative for the study of UHI[14]. However, the impervious surface is a complex land cover and has a heterogeneous characteristic in reflected electromagnetic spectrum. Therefore, it is difficult to be extracted from remote sensing imagery. There are some challenges in identifying impervious surface areas from remotely sensed data[15-18].

The purpose of this study is to assess the surface urban heat island and its associated surface physical characteristics in a rapidly urbanizing area in central China using remote sensing-based approaches. The specific objectives are: (1) to analyze the magnitude and pattern of UHI effects and their changes in the Changsha-Zhuzhou-Xiangtan metropolitan area using land surface temperature derived from MODIS images in different seasons; (2) to compare NDVI with normalized difference built-up index (NDBI) and evaluate the effectiveness of using them as indicators of UHI effects.

1 Study area and data

The Changsha-Zhuzhou-Xiangtan metropolitan area of Hunan, China was chosen as the study area. This area is a key economic, cultural, manufacturing, and transportation center in Hunan province and is one of the largest metropolitan areas in central China (Fig. 1). Because of new economic development policies being implemented in central China, this area is experiencing significant growth. The area expansion is through encroachment into the adjacent agricultural and rural areas. As the area grows, it is important to assess the surface urban heat island effect and its associated surface physical characteristics for the purpose of studying the urban environment and climate in the area as well as plan future development in the area.

To quantitatively measure land surface temperature and detect urban heat island intensity in the study area, TERRA/MODIS images covering the area from different seasons in 2005 were obtained to generate LST maps, NDVI maps and NDBI.

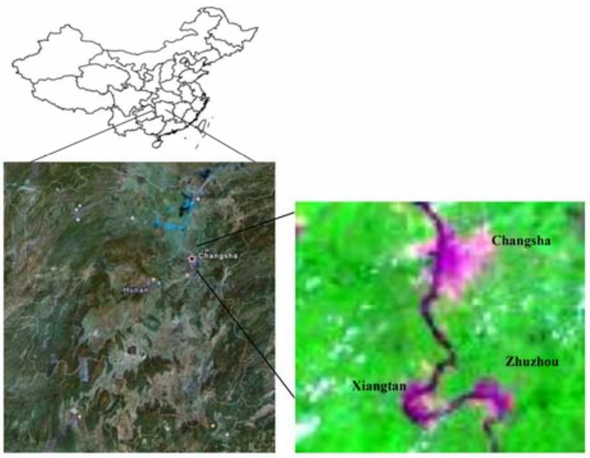

Fig. 1 Location of the Changsha-Zhuzhou-Xiangtan tri- city metropolitan area, Hunan, China

2 Methods

2.1 Computation of land surface temperature

The MODIS thermal infrared bands (bands 31 and 32) data were utilized to derive the land surface temperature. First, at-sensor radiant temperatures for each MODIS band were calculated from emitted spectral radiance using Planck's equation:

$$T_i = \frac{C_2 \upsilon_j}{\mathrm{In}\left(\frac{C_1 \upsilon_j^3}{L_i} + 1\right)} \tag{1}$$

where T_i is the radiant temperature in Kelvin for the pixel in question in band i, C_1 is the calibration constant (1.1910659 ×10^{-5} mWm^{-2} sr^{-1} cm^4), C_2 is the calibration constant (1.438833 cm K), ν_i is the central wave number for each band i, and L_i is the corrected spectral radiance for the pixel in question in band i.

The radiant temperature values computed using Eq. (1) are referenced to an internal black body. MODIS LST was derived from the corrected two thermal bands (bands 31 and 32 in the 10.5-12.5 μm spectra) using split-window LST algorithm for MODIS proposed by Mao et al. (2005)[19]:

$$\mathrm{LST} = (C_{32}(B_{31} + D_{31}) - C_{31}(D_{32} + B_{32})) \\ /(C_{32}A_{31} - C_{31}A_{32}) \tag{2}$$

The coefficients of Eq. (2) are calculated as follows:

$$\begin{aligned}
A_{31} &= 0.13787\varepsilon_{31}\tau_{31} \\
B_{31} &= 0.13787T_{31} + 31.65677\tau_{31}\varepsilon_{31} - 31.65677 \\
C_{31} &= (1-\tau_{31})(1+(1-\varepsilon_{31})\tau_{31})0.13787 \\
D_{31} &= (1-\tau_{31})(1+(1-\varepsilon 31)\tau_{31})31.65677 \\
A_{32} &= 0.11849\varepsilon_{32}\tau_{32} \\
B_{32} &= 0.11849T_{32} + 26.50036\tau_{32}\varepsilon_{32} - 26.50036 \\
C_{32} &= (1-\tau_{32})(1+(1-\varepsilon_{32})\tau_{32})0.11849 \\
D_{32} &= (1-\tau_{32})(1+(1-\varepsilon_{32})\tau_{32})26.50036
\end{aligned} \tag{3}$$

where T_{31} and T_{32} are radiant temperature values of bands 31 and 32; τ_{31} and τ_{32} are the atmospheric transmittance of bands 31 and 32; ε_{31} and ε_{32} are the land surface emissivity at the spectral bands 31 and 32.

2.2 Derivation of land surface and atmospheric parameters

The land surface emissivity is estimated using Eq. (4)

$$\varepsilon_i = P_v R_v \varepsilon_{iv} + (1-P_v) R_s \varepsilon_{is} \tag{4}$$

where ε_{iv} and ε_{is} are vegetation and soil emissivity in band i, respectively; R_v and R_s are the ratio of temperature of vegetation and soil[20]; P_v is vegetation coverage in an image pixel and its value is estimated using NDVI and spectral mixture analysis.

The atmospheric transmittance is calculated as follows:

$$\begin{aligned}
\tau_{31} &= 2.89798 - 1.88366\mathrm{e}^{-(w/-21.22704)} \\
\tau_{32} &= -3.59289 + 4.60414\mathrm{e}^{w/-32.70639}
\end{aligned} \tag{5}$$

where W is the water vapor content and its value is estimated according to the result of Kaufman's study[21].

2.3 Calculation of NDVI and NDBI

The NDVI was derived as follows:

$$\mathrm{NDVI} = \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{red}}}{\rho_{\mathrm{NIR}} + \rho_{\mathrm{red}}} \tag{6}$$

where ρ_{NIR} and ρ_{red} are the spectral reflectance in the MODIS red and near-infrared bands.

The amount of impervious surfaces is an important indicator of urban environmental quality. Therefore, analyzing the relationship between the LST and impervious surface area in an urbanized environment provides an alternative method for studying UHI. However, because the impervious surface is a complex land cover and has heterogeneous landscape characteristics, it is difficult to extract it from remote sensing imageries. The NDBI represents one of the major land cover types, that is, built-up lands, which could describe the spatial pattern of urban impervious surfaces (buildings, roads, parking lots, and other paved surfaces). In this study we investigate the relations between UHI and NDBI. NDBI was derived as follows using Eq. (7) [22]:

$$\mathrm{NDBI} = \frac{\rho_{\mathrm{SWIR}} - \rho_{\mathrm{NIR}}}{\rho_{\mathrm{SWIR}} + \rho_{\mathrm{NIER}}} \quad (7)$$

where ρ_{NIR} and ρ_{SWIR} are the spectral reflectance in the MODIS near-infrared and short wave infrared bands.

3 Results

3.1 UHI spatial patterns and temporal variations

The UHI was recognized using remotely sensed land surface temperature. Three scenes for the Changsha-Zhuzhou-Xiangtan metropolitan area from January to August 2005 were utilized to monitor seasonal variations of UHI. The remote sensing based approach provides not only a measure of the magnitude of land surface temperatures of the entire metropolitan area, but also the spatial extent of the surface urban heat island effects (Fig. 2 (a)). Three apparent heat islands can be identified in the Changsha-Zhuzhou-Xiangtan metropolitan area for different seasons. The summer and spring LST showed striking UHI effects with urban and rural surface temperature contrasts. Among three cities of the metropolitan area, Changsha City has the most intensive urban heat island effects. To better understand the spatial patterns and temporal variations of UHI, we selected Changsha City and delineated North to South (NS) and East to West (EW) transects cutting across the centre of the urban core, respectively. The land surface temperature along these two transects are illustrated in Fig. 3.

The urban-rural temperature differences between the urban center and its surrounding areas (Figs. 2, 3) show a maximum of 10 ℃ difference in temperature in the summer and 8 ℃ in the spring. The spatial extent of UHI effects corresponds to the urban area indicated by NDBI (Fig. 2(c)). The results suggest that UHI effects were significant both in the summer and the spring. Although the UHI existed in the winter, its effects were not as significant as those in the summer and the spring. The land surface temperature in the urban center was 4℃ warmer than that in surrounding rural areas in the winter. The results show that UHIs existed significantly in the Changsha-Zhuzhou-Xiangtan metropolitan area throughout the year. However, the magnitude of UHI effects changed in different seasons. The results implied that the higher temperatures in urban heat islands may increase demands for air conditioning, generate more pollution, and modify precipitation patterns.

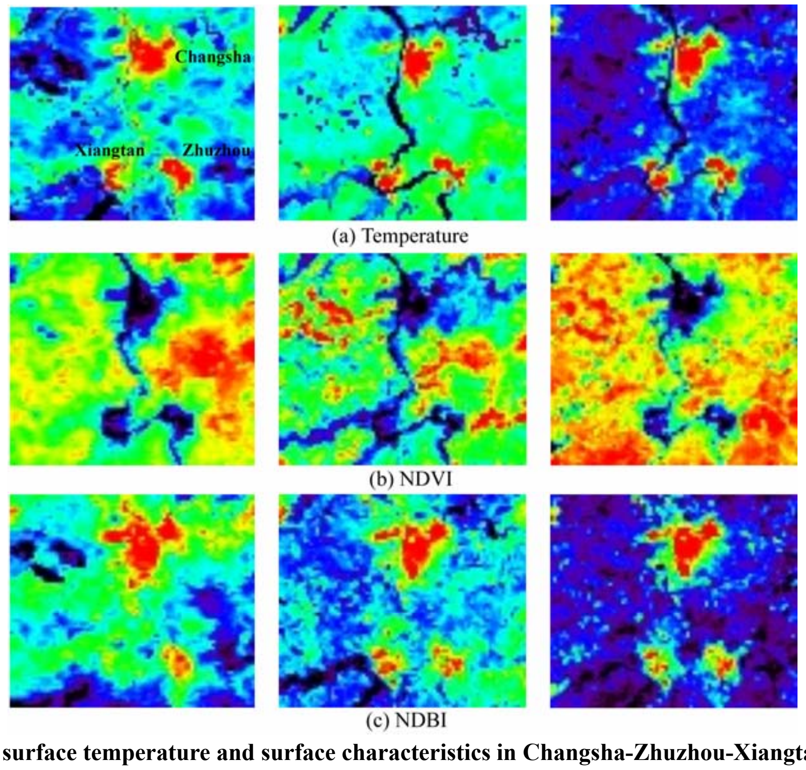

Fig.2 Land surface temperature and surface characteristics in Changsha-Zhuzhou-Xiangtan metropolitan area on Aug. 3, Apr. 21, and Jan.1, 2005

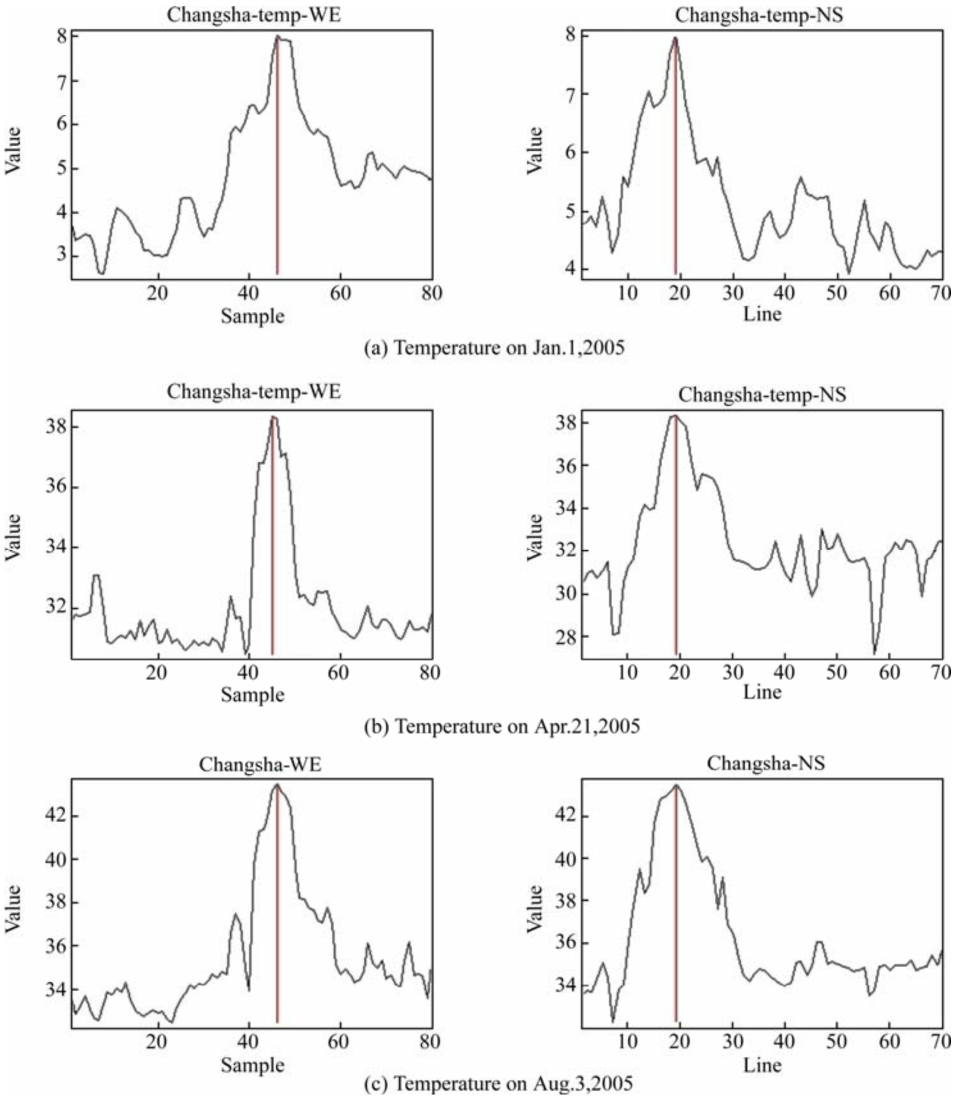

Fig. 3 Land surface temperature along the NS and EW transects cutting across the centre of the urban core in Changsha City

3.2 LST relationship to NDVI and NDBI

To further understand the mechanism for the genesis of UHI and possible changes in climate resulting from urbanization, the relationships between LST and urban surface properties were investigated using all of the pixels in the study area and a sample with 150 points generated along North to South (NS) and East to West (EW) transects cutting across the centre of Changsha City. Both Figs. 4 and 5 indicate that the relationship between LST and NDVI is strongly affected by season and the linear relationship only existed in the summer. Many researchers have studied the temperature-NDVI relationship in the context of urban heat island effects [11, 12]. Because of the variability and nonlinearity of the temperature-NDVI relationship, NDVI alone may not be a sufficient metric for studying UHI quantitatively. The results suggest that NDVI may be only used for the analysis of UHI effects during the summer.

By contrast, as shown in Fig. 5, the consistent linear patterns ($R^2 > 0.7$) between LST and NDBI exist based on analysis results using data the study area. This relationship holds for all the seasons. NDBI is sensitive to the built-up area [22]. Therefore, NDBI can not only be used as an indicator of urban spatial extent and intensity of development, but also as an indicator of urban impervious surface by which sensible heat exchange is favored. The LST was well correlated with the NDBI as indicated by significant positive correlation coefficient of 0.9164, 0.8434, and 0.9143 for the winter, spring, and summer, respectively. The changes of slope and intercept of positive linear correlation between LST and NDBI corresponded to variations of UHI effects in different seasons. The results suggest that NDBI may be used for analyzing UHI effects for all seasons. Therefore, NDBI provides an alternative physical indicator for analyzing LST quantitatively over different seasons, and therefore providing a useful way to study UHI effects using remote sensing.

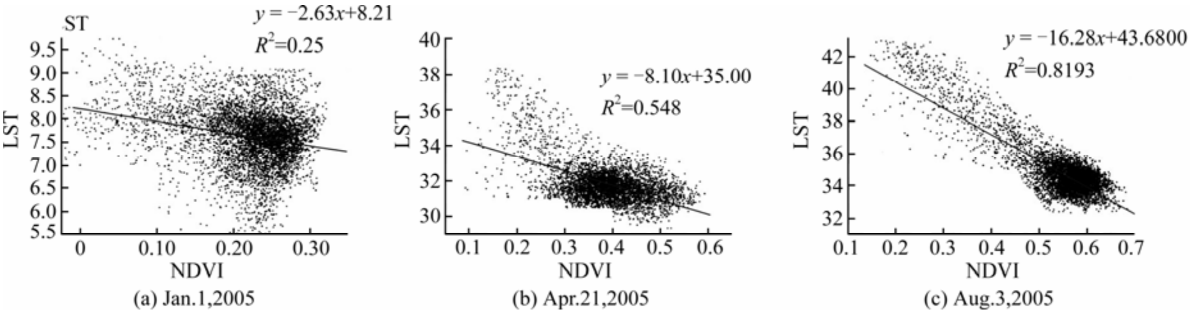

Fig. 4 Scatterplots of LST vs. NDVI for three dates

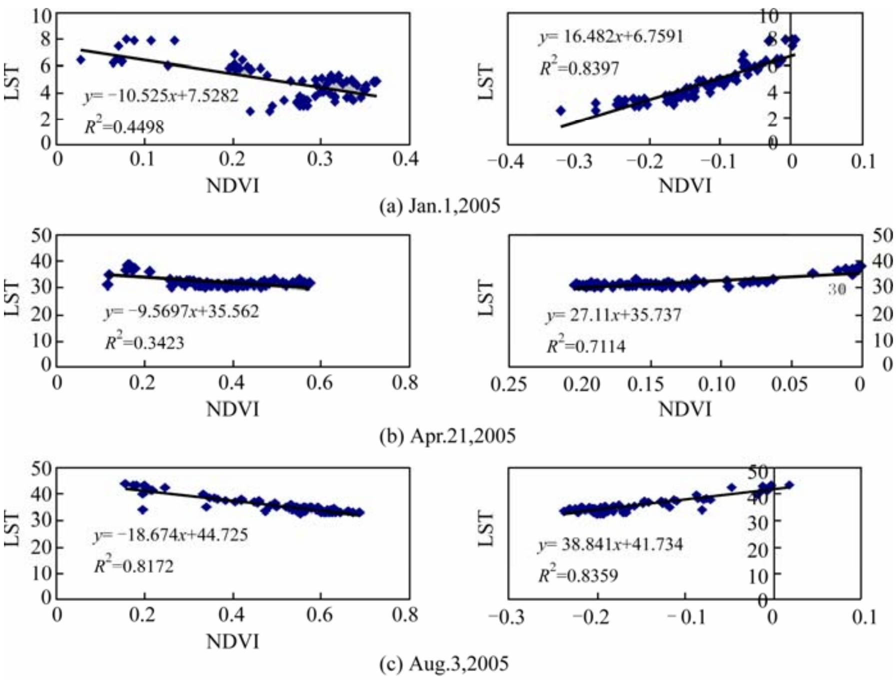

Fig. 5 LST relationship to NDVI and NDBI in different seasons

4 Conclusion

The study quantitatively assessed the UHI spatial patterns and temporal variations in the Changsha-Zhuzhou-Xiangtan metropolitan area, a rapidly developing area in central China. The results showed that UHIs existed significantly in the area throughout the year. However, the magnitude of UHI effects changed in different seasons. The urban-rural temperature differences between the urban core and its surrounding areas show a maximum difference of 10℃ in the summer and 8℃ in the spring. The results implied that higher temperatures in urban heat islands would increase demands for air conditioning, generate more pollution, and may modify precipitation patterns.

To further understand the mechanism for the genesis of UHI, the relationship between LST and urban surface properties were investigated. The results indicate that the relationship between LST and NDVI is strongly affected by season. Because of the variability and nonlinearity of the temperature-NDVI relationship, NDVI alone may not be a sufficient metric for studying UHI quantitatively. By contrast, the consistent linear patterns between LST and NDBI existed in the study area for all the seasons. The results suggest that NDBI may be used for analyzing UHI effects for all seasons and it may serve as a sufficient metric to study UHI quantitatively. The amount of slope and intercept of the linear relationship can indicate the magnitude of UHI for different seasons.

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