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Influences of land cover types, meteorological conditions, anthropogenic heat and urban area on surface urban heat island in the Yangtze River Delta Urban Agglomeration

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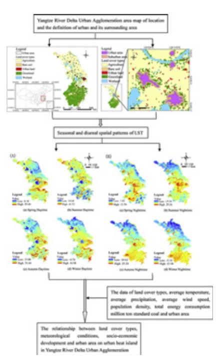
HIGHLIGHTS

- It is necessary to explore the driving factors of UHI to develop mitigating measures and reasonable urban plans.
- The UHI intensity in the Yangtze River Delta Urban Agglomeration was the strongest (0.84 °C) in summer, followed by 0.81 °C in autumn, 0.78 °C in spring, and 0.53 °C in winter.
- The daytime UHI intensity is higher than the nighttime UHI intensity.
- There is no significant correlation between population density and UHI intensity in the Yangtze River Delta Urban Agglomeration.
- Energy consumption, average temperature, and urban area were significantly positively correlated with UHI intensity.
- The average wind speed and average precipitation was significantly negatively correlated with UHI intensity.

GRAPHICAL ABSTRACT



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ABSTRACT

Urban heat islands (UHIs) reflect the localized impact of human activities on thermal fields. In this study, we assessed the surface UHI and its relationship with types of land, meteorological conditions, anthropogenic heat sources and urban areas in the Yangtze River Delta Urban Agglomeration (YRDUA) with the aid of remote sensing data, statistical data and meteorological data. The results showed that the UHI intensity in YRDUA was the strongest (0.84 °C) in summer, followed by 0.81 °C in autumn, 0.78 °C in spring and 0.53 °C in winter. The daytime UHI intensity is 0.98 °C, which is higher than the nighttime UHI intensity of 0.50 °C. Then, the relationship between the UHI intensity and several factors such as meteorological conditions, anthropogenic heat sources and the urban area were analysed. The results indicated that there was an insignificant correlation between population density and the UHI intensity. Energy consumption, average temperature and urban area had a significant positive correlation with UHI intensity. However, the average wind speed and average precipitation were significantly negatively correlated with UHI intensity. This study provides insight into the regional climate characteristics and a scientific basis for city layout.

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1. Introduction

According to the World Urbanization Prospects released by the United Nations in 2014, 54% of the world's population lives in urban areas, and this number will reach 66% by 2050 (United Nations, 2014). The accelerating urbanization process leads to rapid growth in the population and in the number of new buildings. Natural land surfaces are gradually replaced by impervious surfaces, such as cement, asphalt and concrete (Quattrochi and Luvall, 1997). This change leads to different exchange processes of water, substances and energy between the land surface and the atmosphere. Subsequently, a special micro-climate effect forms and introduces higher temperatures in the urban area than its surroundings. The effect is called the "urban heat island (UHI) effect" (Oke, 1973). Because the UHI is closely related to land cover types (LCTs), meteorological conditions, anthropogenic heat sources and the size of the urban area (Peng et al., 2012; Coseo and Larsen, 2014; Debbage and Shepherd, 2015; Guo et al., 2015; Tan and Li, 2015), it is necessary to explore the driving factors of UHI to direct scientific urban planning such as appropriate distribution of industries among cities and specially designed internal streets to help dissipate the heat.

The study of UHI effects involves all stages of development: single city, mega-city and city agglomeration. Along with these stages, research methods have also improved continuously. Early UHI research is based on meteorological observations. By analysing the observed data, the air temperature difference between urban and suburban developments is studied. This difference is called the air UHI (Arnfield, 2003). Because the observation sites are sparsely distributed, it is difficult to obtain a complete spatial distribution for the heat near the ground. In recent years, satellite remote sensing technology has developed rapidly. With the advantages of wide coverage, intuitive images and good synchronization, the technology has widely been applied in the research on UHIs and plays an increasingly important role in this field (Wan, 2008; Imhoff et al., 2010). Studies of UHIs are processed by deriving land surface temperature (LST) from the satellite images. The result is usually called the surface UHI (Voogt and Oke, 2003; Chen et al., 2014).

UHIs of single cities and mega-cities have been widely studied (Unger, 1996; Targino et al., 2014). The UHI intensity and its seasonal changes in mega-cities such as Beijing, Shanghai, Sao Paulo and Mexico City have also been explored (Cai et al., 2011; Jauregui, 1997; Ferreira et al., 2013; Zhang et al., 2010). However, UHI studies on city agglomerations remain in need of strengthening (Peng et al., 2012; Zhou et al., 2013). Urban agglomeration is an extended city or town area comprising the build-up of a central place (usually a municipality) and suburbs linked by continuous urban areas. With the continuous urbanization process, the distance between cities decreases or even disappears; thus, city agglomerations are formed. City agglomerations could change the regional thermal environment by raising the temperature in a continuous area and thus impacting the ecological environment. Therefore, it is necessary to increase the amount of study on the UHI of city agglomerations to understand such regional climate characteristics. Then, a scientific basis for a regional city layout could be provided.

The driving factors of UHI intensity have been studied widely. These factors include LCT, meteorological conditions, anthropogenic heat release and urban morphology (Nichol, 2005; Hung et al., 2006; Grimm et al., 2008). Stabler et al. (2005) noted that urban micro-climates were greatly influenced by variations in vegetation cover. Gedzelman et al. (2003) explored the UHI of New York City and found that the UHI was significantly correlated with the wind speed, wind direction, cloud cover and surface temperature. Elsayed (2012) showed that UHI intensity correlated significantly with population density. In addition, Lemonsu et al. (2015) reported that the UHI was impacted by morphologies of the city such as size, shape, composition and arrangement of its neighbourhoods. Tan and Li (2015) studied the UHI of the Hebei Plain in Northern China and found that UHIs increased with cluster size and this relationship could be approximated by a logarithmic function. Most of the previous research focused on single variable analysis (Oke, 1973; Jusuf et al., 2007; Imhoff et al., 2010; Tan and Li, 2015), and the influence of multiple factors on the UHI of city agglomerations were seldom reported (Peng et al., 2012; Coseo and Larsen, 2014).

The Yangtze River Delta Urban Agglomeration (YRDUA) is one of the most developed, densely populated and concentrated industrial areas in China. In the YRDUA, cities and regions are closely linked with each other. The diversity and spatial heterogeneity of land surface conditions, dense population and close connection of city regions makes the YRDUA an ideal area for the study of city agglomeration UHIs. This study aims to examine the seasonal variations in LST with different LCT and to explore the relationship between surface UHI intensity and influencing factors (meteorological conditions, anthropogenic heat release and urban area). This enhances the understanding of the driving factors of UHIs and provides corresponding mitigation measures.

2. Study area

The YRDUA is one of six influential world-class metropolitan areas and plays an important role in Chinese economic and social development (Tian et al., 2011). It is located along the central-eastern coastline of China (Fig. 1). The region belongs to an alluvial plain with a long agricultural history and moderate climate. The boundaries of what constitutes the Yangtze River Delta (YRD) are different based on different perspectives in culture, economy and geography. In this paper, the YRD refers to the area composed of Shanghai, Jiangsu Province and northern Zhejiang Province, including 11 big cities (urban populations exceeding 1 million), 51 cities (urban population from 0.5 to 1 million) and 39 counties (urban population smaller than 0.5 million) (Table 1). This region is one of the most developed, densely populated and concentrated industrial areas in China. It covers an area of 239,528 km^2, and the population is 139.2 million. The average population density is 581 people/km^2 (Table 1).

3. Data and methods

3.1. Data

In this study, four major data sets were used: LST, LCT, (average wind speed and average air temperature) and the statistical census data from 2014 (population and total energy consumption).

The LST data, at a spatial resolution of 1000 m, were obtained from Terra-MODIS composite products (MOD11A2). The retrieval of LST was improved by correcting for noise caused by cloud contamination, topographic differences and zenith angle changes (Wan, 2008). The

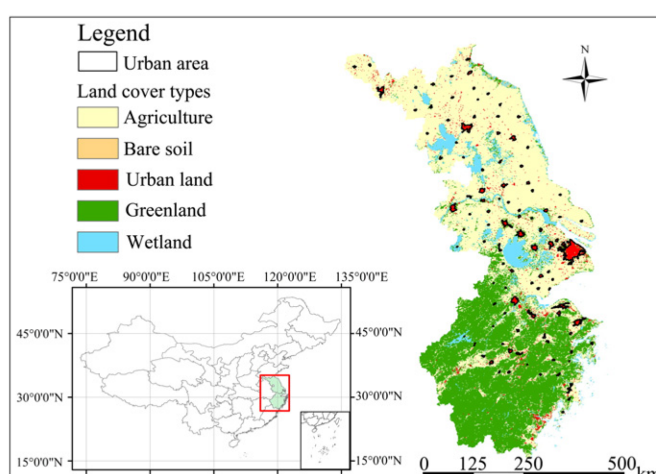

Fig. 1. The location and land cover types of the YRDUA (YRDUA: Yangtze River Delta Urban Agglomeration).

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Table 1
Statistical information of the YRD (Yangtze River Delta) in 2014.
Sources: Shanghai Statistical Yearbook 2015, Jiangsu Statistical Yearbook 2015 and Zhejiang Statistical Yearbook 2015.

Categories	Value
Big-city (number)	11
City (number)	51
County (number)	39
Area (km^2)	239,528
Population (million)	139.2
Population density (people/km^2)	581

validation of the in situ LST data measurements indicate that the accuracy of the MODIS LST data were better than 1 °C in most cases (Wan, 2008).

The LCT data were obtained from the MODIS Global Land Cover Type data of 2013, with a spatial resolution of 500 m. To remain consistent with LST spatial resolution, the LCT map resolution was resampled to 1000 m. In this study, the LCT was re-grouped into five types: urban land, agricultural land, green land, wetland and bare soil.

The monthly average wind speed, average precipitation and average air temperature of each city were obtained from the meteorological data archive of the Chinese Meteorological Administration.

The 2014 statistical data on urban population and total energy consumption were obtained from statistical yearbooks, including the 2015 Shanghai Statistical Yearbook (Shanghai Statistics Bureau, 2015), 2015 Jiangsu Statistical Yearbook (Jiangsu Statistics Bureau, 2015) and the 2015 Zhejiang Statistical Yearbook (Zhejiang Statistics Bureau, 2015).

3.2. Methods

UHI intensity was defined as the temperature difference between urban areas and their surroundings. In this study, big cities, cities and counties were all regarded as urban areas. Thus, 101 urban areas were selected (Fig. 1). After the urban areas were determined and the wetland within the ring zone around the urban area was excluded (Peng et al., 2012; Zhou et al., 2013), suburban areas were determined (Fig. 2). Both the annual average seasonal and diurnal surface temperatures were computed from MODIS LST (Wan, 2008). The four seasons are defined as follows: spring is from March to May; summer is from June to August; autumn is from September to November; winter is from December to February. The UHI intensity can be calculated using Eq. (1).

$$\text{UHI intensity } (^\circ\text{C}) = T_{\text{Urban Average}} - T_{\text{Suburban Average}} \quad (1)$$

Three meteorological parameters (average wind speed, average precipitation and average air temperature), two anthropogenic heat parameters (population density and total energy consumption) and one urban morphology parameter (size of urban area in km^2) were selected as the indicator variables. Linear regressive analyses were performed in SPSS19.0 to characterize the driving factors and UHI intensity.

4. Results

The spatial distribution of surface temperatures shows significant seasonal and diurnal differences in the YRDUA (Fig. 3). The LSTs of various LCTs are significantly different (Table 2). We computed the mean and standard deviation (STDEV) values of LSTs for various LCTs. The STDEV value was used to estimate the standard deviation of the LST for the LCT and reflects the degree of dispersion related to the mean value. In all seasons, the daytime average temperature is the highest in urban areas and the lowest in wetlands. At nighttime, except for in the summer, the average temperature is the highest in wetlands and the lowest in agricultural lands. During summer nights, the temperature is the highest in urban areas, followed by wetlands and then bare soil.

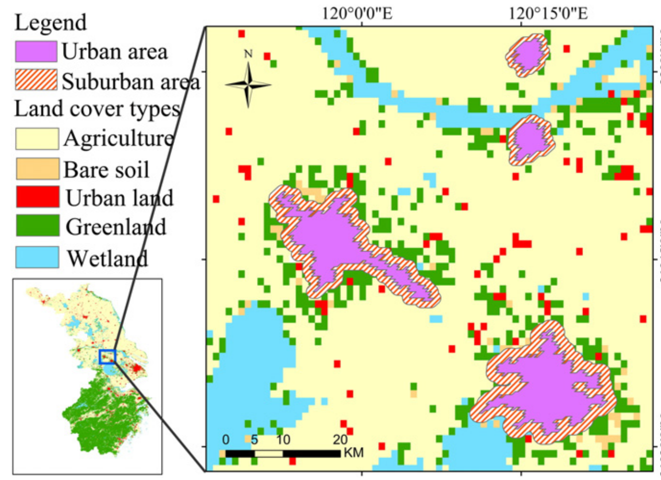

Fig. 2. A map of urban and surrounding areas. Purple area represents the urban areas. Shaded area represents the suburban areas. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3 summarizes the average seasonal and diurnal UHI intensity in the YRDUA. The summer daytime UHI intensity is the highest (1.12 °C); the winter nighttime UHI intensity is the lowest (0.40 °C). Overall, the UHI intensity in YRDUA is the highest in summer at 0.84 °C, followed by 0.81 °C in autumn, 0.78 °C in spring and 0.53 °C in winter. The daytime UHI intensity is 0.98 °C, which is higher than the nighttime UHI intensity of 0.50 °C.

As shown in Fig. 4, the correlation between the UHI intensity and population density is insignificant ($P > 0.05$). A previous study by Debbage and Shepherd (2015) also indicated that city population density had a minimal influence on UHI intensity.

Previous studies indicate that emission of carbon dioxide contributes to global warming, and enhances the UHI effect (Grimmond, 2007). In cities, energy consumption is the main source of anthropogenic CO_2 emissions and an important driving factor for the thermal environment (McCarthy et al., 2010). Therefore, the relationship between energy consumption and UHI intensity can reflect the impact of anthropogenic heat on UHI intensity.

As shown in Fig. 5, UHI intensity is significantly positively correlated with energy consumption ($P < 0.001$). The larger the energy consumption is, the more significant the UHI intensity is. Compared to daytime energy consumption ($R^2 = 0.219$), nighttime energy consumption ($R^2 = 0.228$) can explain UHI intensity to a greater degree.

As shown in Fig. 6, the UHI intensity has a significant positive correlation with the average temperature in each season ($P < 0.001$). In spring and winter, nighttime energy consumption contributes more to the UHI intensity to a greater degree. However, in summer and autumn, daytime energy consumption contributes more to the interpretation of UHI intensity.

UHI intensity was found to have significantly negative correlations with average wind speed (Fig. 7). In the daytime, the R^2 values reach 0.619 and 0.617 in spring and winter, respectively. This means that the wind speed can explain >60% of the variance in UHI intensity because R^2 is the percentage of the explainable variation (dependent variable).

As shown in Fig. 8, UHI intensity is negatively correlated with the average precipitation in each season ($P < 0.001$). This means that as the precipitation increases, UHI intensity for both the daytime and nighttime decreases. The precipitation data better explain its impact on UHI effects in summer and during daytime than in winter and during nighttime.

We also tested whether the surface heat islands were related to the urban areas. Except in summer's daytime, the UHI intensity is significantly positively correlated with urban area ($P < 0.01$, Fig. 9). This means that as the amount of urban area increases, the UHI intensities for both daytime

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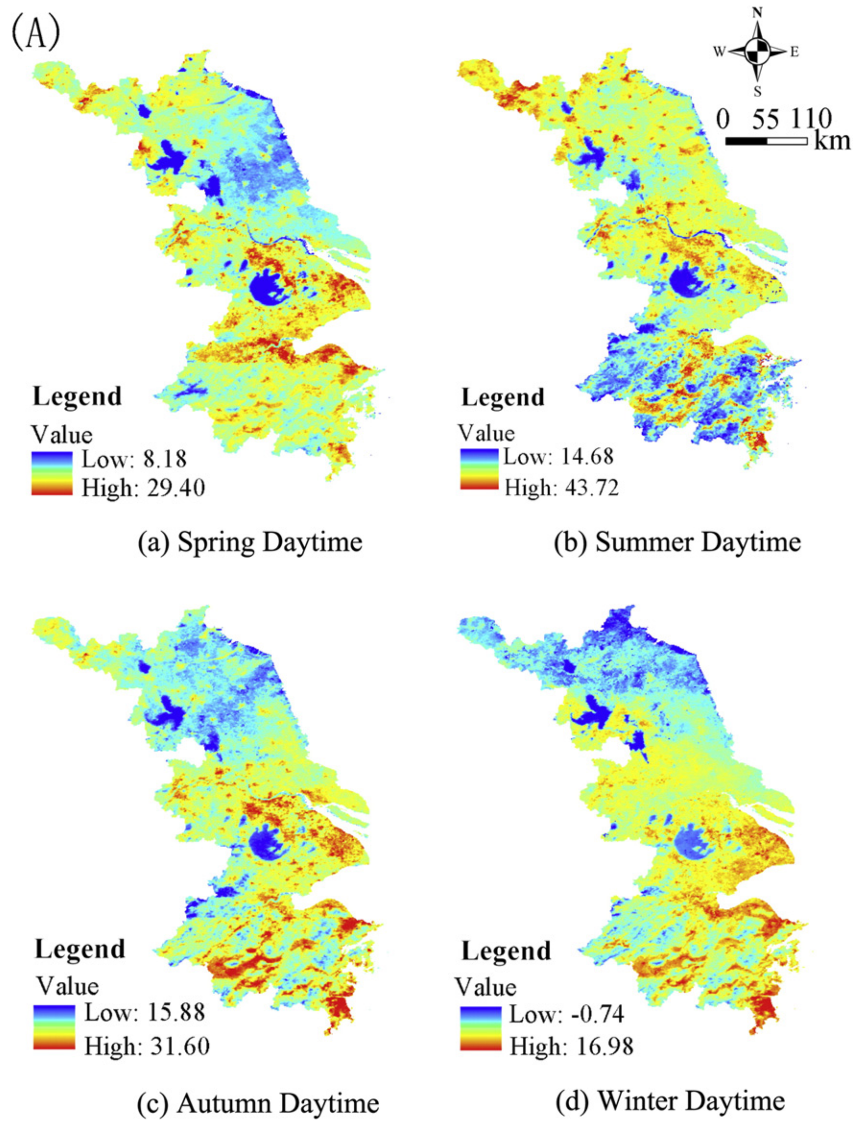

Fig. 3. (A) Seasonal spatial patterns of daytime LST (°C) and (B) nighttime LST (°C) in the YRDUA, 2014. (LST: Land Surface Temperature. YRDUA: Yangtze River Delta Urban Agglomeration).

and nighttime rapidly increase. There is no significant correlation between the amount of urban area and the UHI intensity during summer days ($P = 0.166$).

5. Discussion

5.1. UHI intensity and LCT

The general LSTs vary with LCTs due to differences in artificial heat sources and the thermal-biological variations of surface materials (Su and Yang, 2010).

In the daytime, surface heat storage is related to thermal properties and solar energy absorption (Peng et al., 2012). Urban areas have a smaller reflectivity than other LCTs. They can absorb more radiation, solar energy and release less evaporative energy (Kjelgren and Thayne, 1998). However, wetlands have low thermal conductivity and emissivity (Imhoff et al., 2010). The temperature is higher in urban areas and lower in wetlands during the daytime.

During the night, the surface temperature is related to the latent heat flux from the surface to the atmosphere (Voogt and Oke, 2003). Wetlands have a higher temperature at this time (Imhoff et al., 2010) because water has a high thermal capacity and inertia, and this makes the wetlands release heat slowly. Agricultural lands, however, have low temperatures. The difference may be due to three factors. First, agricultural land is composed of sparse vegetation and exposed bare soil, which has a low thermal capacity and inertia, and thus releases heat quickly at night, decreasing the temperature (Weng, 2001). Second, large agricultural areas are also situated in relatively empty spaces. Therefore, the long-wave radiation from the ground can be easily scattered into the atmosphere and reduce the LST (Chudnovsky et al., 2004). Third, with sufficient soil moisture, plant roots can absorb soil moisture and emit it into the atmosphere through transpiration, thus reducing the LST. In urban areas, the underlying surfaces are mainly made of impervious materials, such as cement, asphalt, brick and metals, which have low water-retention rates and specific heats (Kjelgren and Thayne, 1998) and release a large amount of heat quickly at night, thus readily reducing the LST.

As expected, the surface temperature difference in the daytime was the greatest, and the summer UHI was significantly larger than the winter UHI (Imhoff et al., 2010; Peng et al., 2012). The strong UHI intensity in summer and the weak UHI intensity in winter may be a result of two different factors. First, urban land surfaces have lower water

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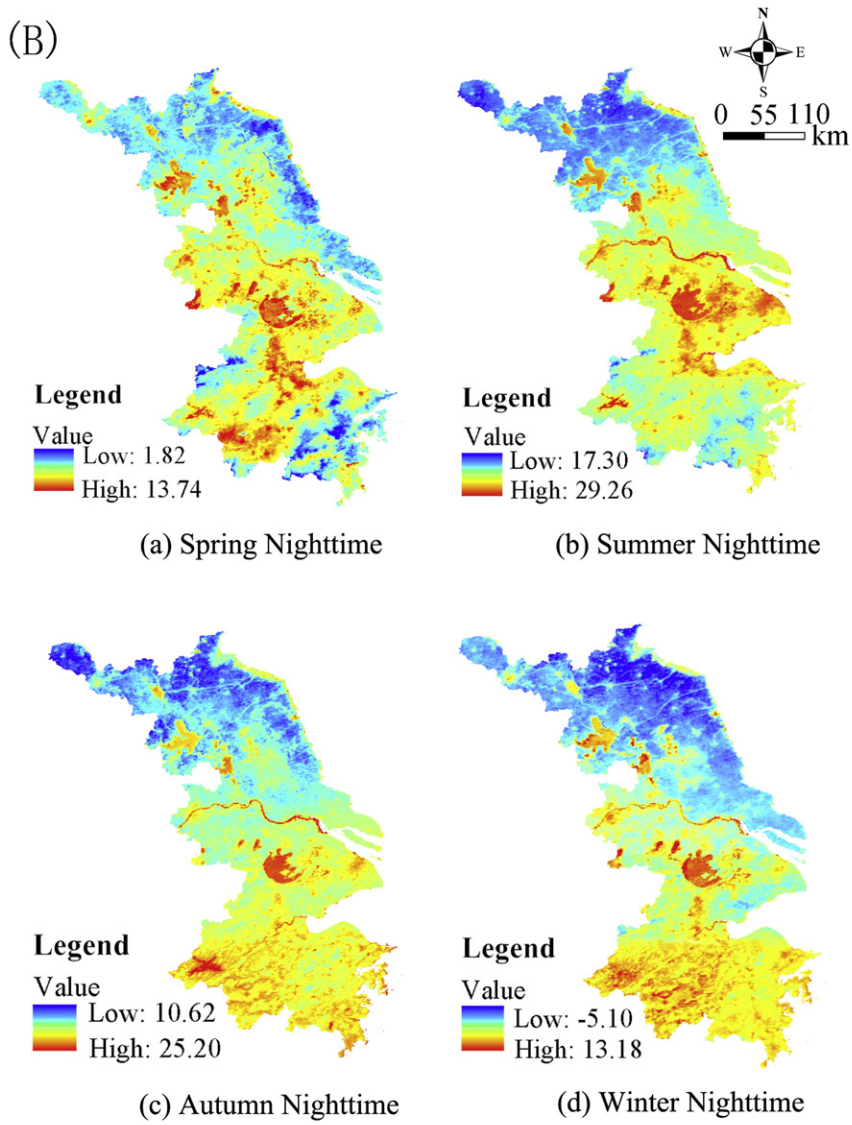

Fig. 3 (*continued*).

permeabilities, making their thermal properties different from those of suburban areas. The result is a higher heating rate in the urban area than in suburban areas (Holmer et al., 2007; Targino et al., 2014). Moreover, agricultural land in suburban areas has a higher degree of vegetation coverage and soil water content. This helps release a large amount of heat by evaporation and increases the LST difference between urban and suburban areas. Second, as the YRDUA is located in the northern hemisphere with a low solar altitude in winter, tall buildings easily form shadows, which reduces the amount of shortwave radiation, decreasing the LST in urban areas.

The UHI intensity in the daytime is higher than that in the nighttime. This difference may be interpreted as being a result of three factors. First, there is a significant difference in the thermal

Table 2
Temperature in different seasons in different LCTs (mean ± SD, °C).

		Wetland	Bare soil	Urban land	Greenland	Agricultural land	YRDUA
Daytime	Spring (°C)	15.43 ± 3.71	17.84 ± 3.97	21.52 ± 3.91	18.45 ± 4.12	19.3 ± 4.17	18.50 ± 4.52
	Summer (°C)	28.37 ± 3.12	29.74 ± 3.21	32.41 ± 3.14	29.43 ± 4.57	31.11 ± 4.17	30.23 ± 3.76
	Autumn (°C)	21.06 ± 2.65	23.17 ± 2.65	25.10 ± 2.91	23.56 ± 3.72	24.70 ± 3.65	24.11 ± 3.52
	Winter (°C)	9.15 ± 3.11	9.56 ± 2.49	10.67 ± 3.18	10.22 ± 4.06	10.49 ± 3.21	10.06 ± 4.01
	Average (°C)	18.72 ± 7.72	20.37 ± 8.14	22.53 ± 8.05	21.11 ± 8.23	21.68 ± 8.19	
Nighttime	Spring (°C)	9.21 ± 2.54	8.25 ± 2.02	7.60 ± 2.73	8.07 ± 2.49	6.71 ± 2.43	7.91 ± 2.79
	Summer (°C)	23.81 ± 2.01	23.64 ± 1.36	24.77 ± 2.75	22.75 ± 3.02	23.48 ± 2.88	23.66 ± 2.31
	Autumn (°C)	18.72 ± 2.17	18.54 ± 1.54	16.92 ± 2.89	17.37 ± 2.68	16.10 ± 3.02	17.41 ± 2.64
	Winter (°C)	5.23 ± 3.95	3.92 ± 2.08	2.08 ± 3.57	4.52 ± 3.16	1.42 ± 3.91	3.40 ± 4.22
	Average (°C)	13.13 ± 8.13	13.21 ± 9.02	12.09 ± 8.85	12.74 ± 8.33	11.23 ± 8.97	

Note: LCT: Land Cover Type, YRDUA: Yangtze River Delta Urban Agglomeration.

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Table 3
Seasonal and diurnal UHI intensity (°C).

	Spring	Summer	Autumn	Winter	Diurnal average
Daytime (°C)	1.06	1.12	1.08	0.66	0.98
Nighttime (°C)	0.50	0.55	0.54	0.40	0.50
Seasonal average (°C)	0.78	0.84	0.81	0.53	

Note: UHI: urban heat island.

absorption and storage between urban and suburban areas. Compared to a suburban area, the urban underlying surface has a higher sunlight absorption rate, larger heat capacity and higher heat conductivity and can absorb and store large amounts of heat more quickly (Jin et al., 2011) than a suburban area. Second, urban areas have denser levels of architecture and less access to the sky. The ground's long-wave radiation experiences multiple reflections between the walls and surfaces in urban areas, and so heat loss from the ground to the atmosphere is greatly reduced (Kalnay and Cai, 2003). These results are consistent with previous findings (Peng et al., 2012) in that the average annual daytime UHII (1.5 ± 1.2 °C) was higher than the annual nighttime UHII (1.1 ± 0.5 °C; $P < 0.001$).

5.2. UHI intensity and meteorological conditions

In our study, UHI intensity had a significant positive correlation with average temperature and significantly negative correlations with the average wind speed and average precipitation in all four seasons. UHI intensity is significantly correlated with average temperature (Fig. 6). Land surface materials are greatly influenced by environmental temperature. Urban land surface materials mainly include asphalt, tile and concrete, which have high heat flux and thermal inertia and are greatly influenced by environmental temperatures (Debbage and Shepherd, 2015). However, suburban land surface materials mainly include bare soil and vegetation with low heat flux and thermal inertia and are therefore less influenced by the environmental temperature than are urban land surface materials (Oke, 1973).

According to Fig. 7, the UHI intensity in spring and winter is significantly correlated with average wind speed. The low temperatures and heavy winds accelerate temperature exchange between urban and suburban areas during spring and winter in the YRDUA, thus reducing the UHI intensity (Peng et al., 2012).

UHI intensity in all four seasons is significantly correlated with average precipitation (Fig. 8). This agrees with the previous research findings of Peng et al. (2012). There are usually heavy clouds that block the sun during the precipitation processes; this helps decrease the LST difference between urban and sub-urban areas (Zhou and Shu, 1994).

5.3. UHI intensity and anthropogenic heat

Rizwan et al. (2008) and Sailor (2011) reported that anthropogenic heat release also contributes to maintaining UHI intensity. Anthropogenic heat mainly includes the heat generated by energy consumption and human physiological metabolism (Ichinose et al., 1999; Sailor and Lu, 2004). Energy consumption and population density were chosen as indicators of anthropogenic heat.

The UHI intensity is significantly positively correlated with energy consumption. Higher levels of energy consumption indicate higher UHI intensity. All energy consumption processes in daily life regularly emit a large amount of heat, dust and greenhouse gases into the atmosphere, thus raising the air temperature. The emitted heat is supplied directly to the surface layer of the atmosphere. Therefore, the urban temperature rises, and the UHI intensity is aggravated (Fulton, 1984). In the energy consumption process, a large amount of greenhouse gases and sooty dusts are released, covering the urban areas, increasing the land surface's longwave radiation absorption and aggravating UHI intensity (Arnfield, 2003).

The average UHI intensity of the YRDUA is not significantly correlated with population density. The reason may be that metabolic heat accounts for only a very small fraction of the urban anthropogenic heat and so contributes little to UHIs (Peng et al., 2012). This result lends some support to the research of Oke (1973) and Park (1986).

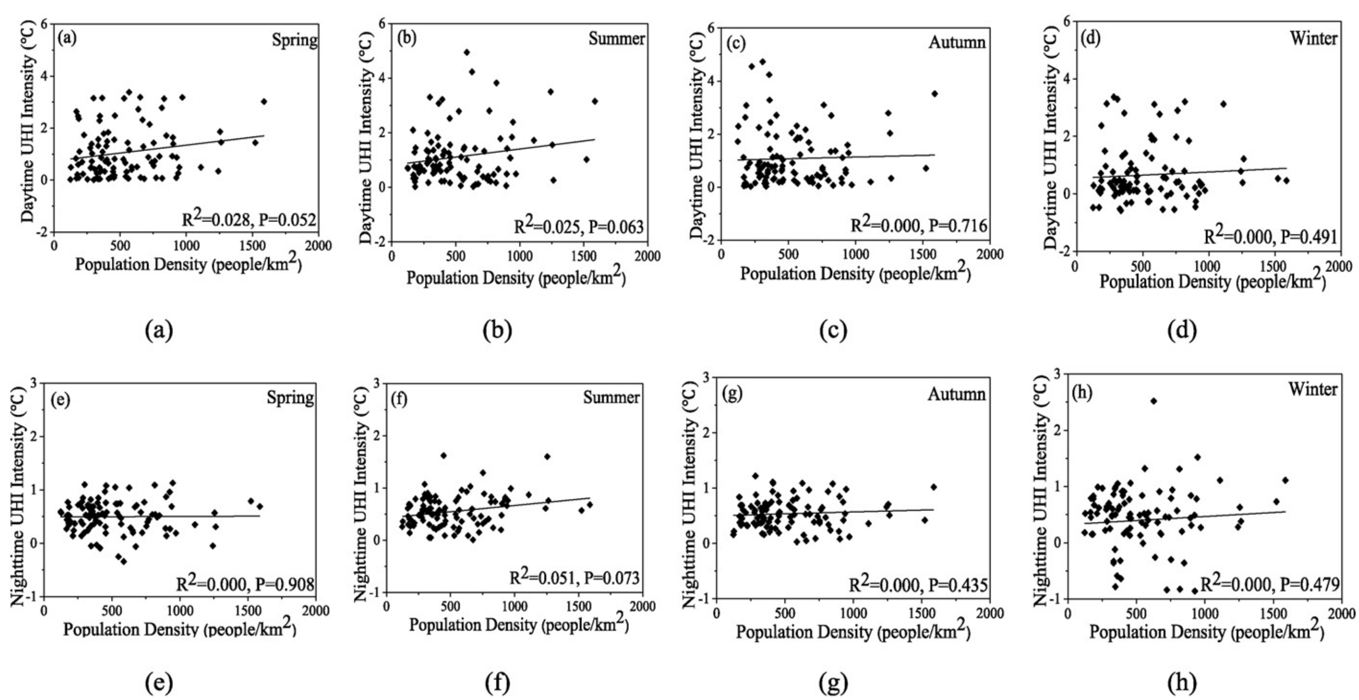

Fig. 4. (a)–(h) Correlations between average UHI intensity and population density.

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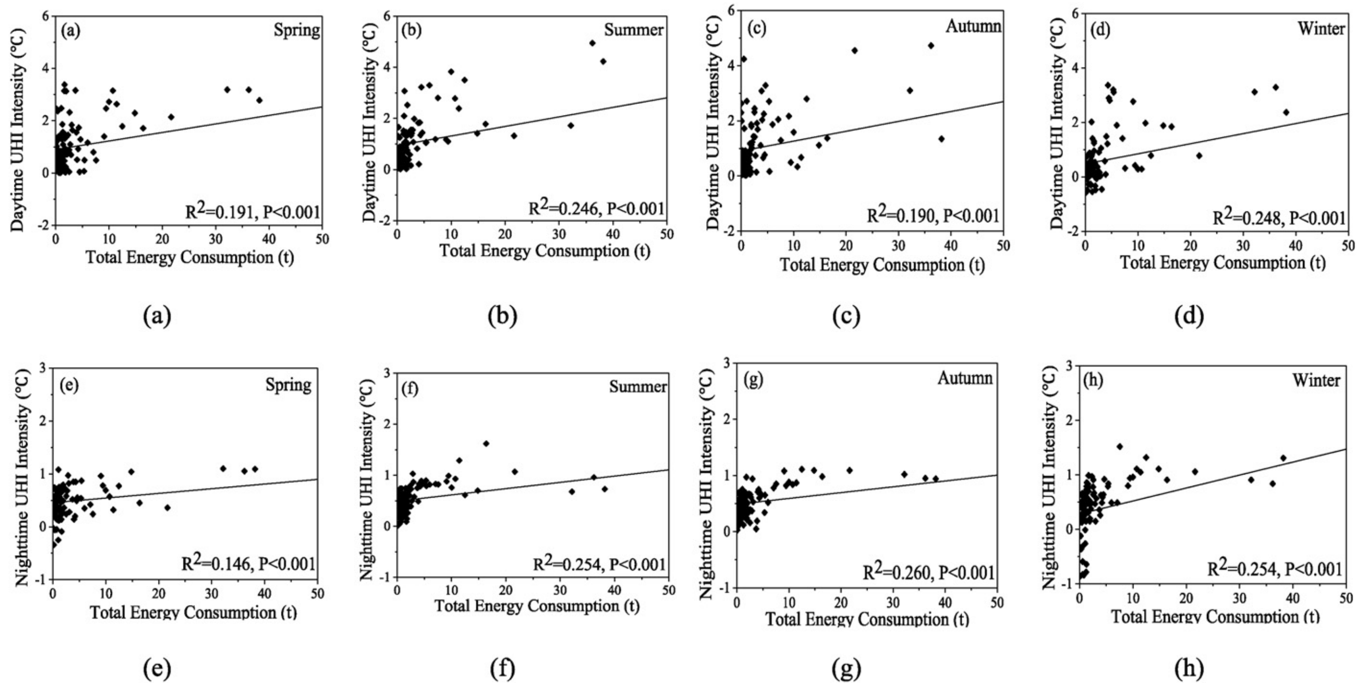

Fig. 5. (a)–(h) Correlations between average UHI intensity and total energy consumption.

5.4. UHI intensity and urban area

In our study, UHI intensity positively correlated with the amount of urban area. The correlation may be interpreted as follows: a larger urban area generally has more impervious surfaces, which can absorb more heat and raise the urban temperature (Imhoff et al., 2010; Cai et al., 2011). Larger urban areas always mean a developed regional economy and higher energy consumption, which can expand the temperature gap between urban and suburban areas and increase the UHI intensity (Fulton, 1984). Similarly, Tan and Li (2015) also concluded that UHI intensity increased with increases in the urban area in the Hebei Plain in Northern China.

The results show that there is a weak correlation between urban areas and UHI intensity in the summer. The weak correlation may be interpreted as follows: the environmental temperature in the summer is high, so the UHI intensity mainly depends on environmental temperatures. Thus, the correlation between urban area and the UHI intensity is weakened.

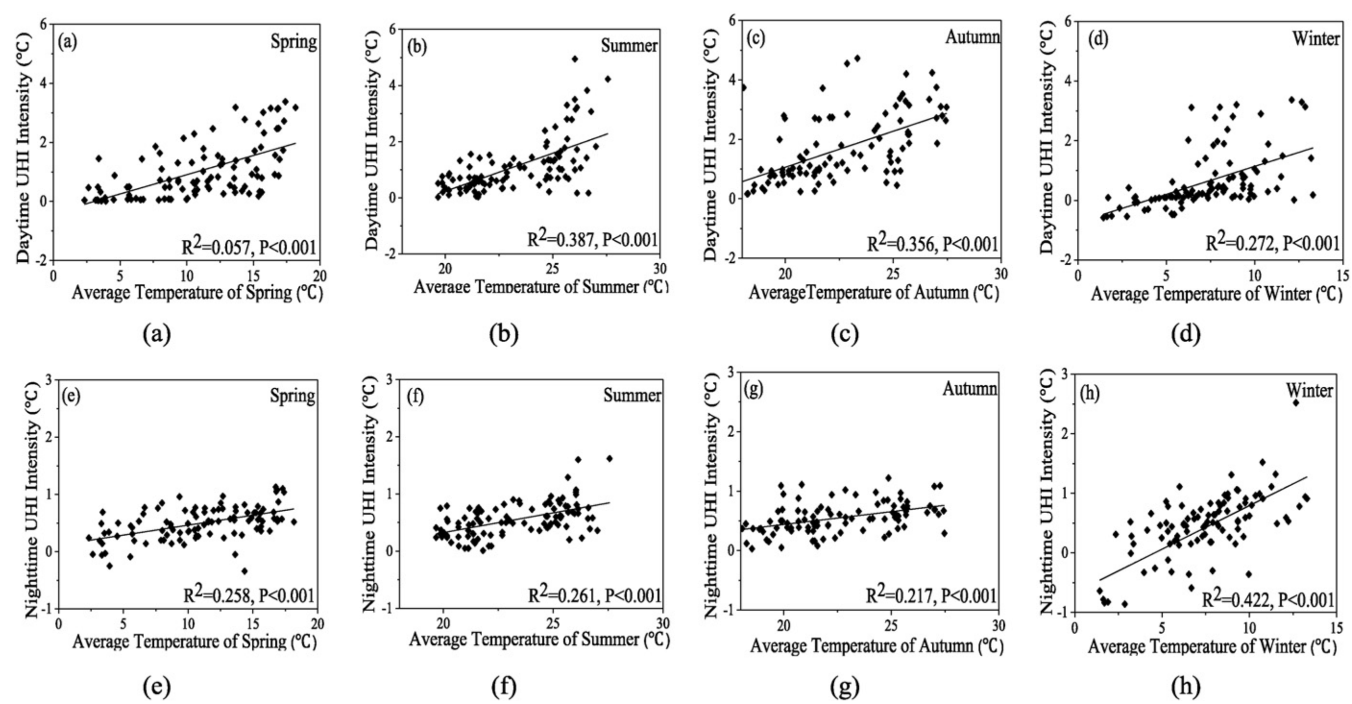

Fig. 6. (a)–(h) Correlations between average UHI intensity and average temperature.

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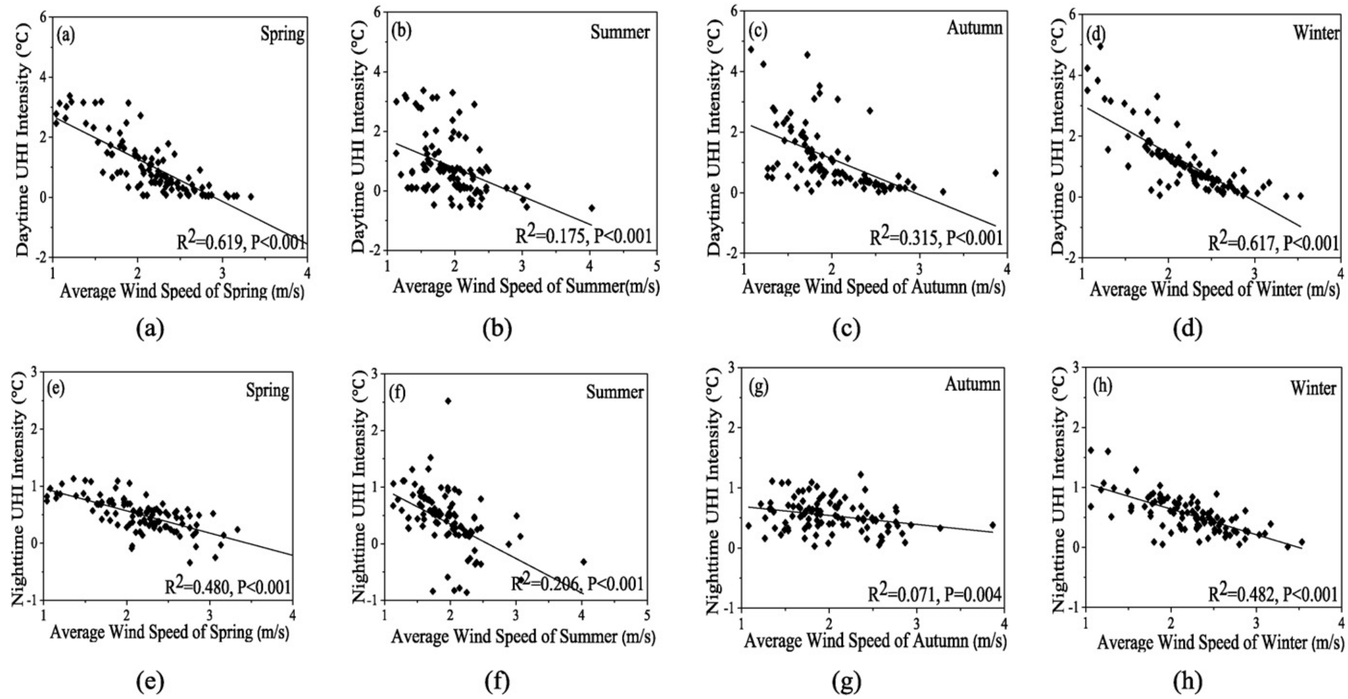

Fig. 7. (a)–(h) Correlations between average UHI intensity and average wind speed.

6. Conclusions

In this study, based on remote sensing data, statistical data and meteorological data, we assessed the UHI and its relationship with LCT, meteorological conditions, socio-economic development and urban area in the YRDUA. The LCT affects the LST. This means that land use planning should be a critical consideration factor in the future. Therefore, in the future for urban planning and design, designers should strengthen the construction of ecological corridors to facilitate mass and energy exchange between urban areas and their surroundings. Through scientific urban layout, we can achieve UHI mitigation.

UHI intensity significantly positively correlates with energy consumption and urban areas. To mitigate the UHI effect in the YRDUA, it is necessary to control the increase in the amount of urban area and energy consumption by developing new towns to disperse urban overspill, improving the combustion efficiency of fuel and advocating for public transportation.

In this study, we explored the influencing factors of UHI in an urban agglomeration and analysed the diurnal UHI intensity in

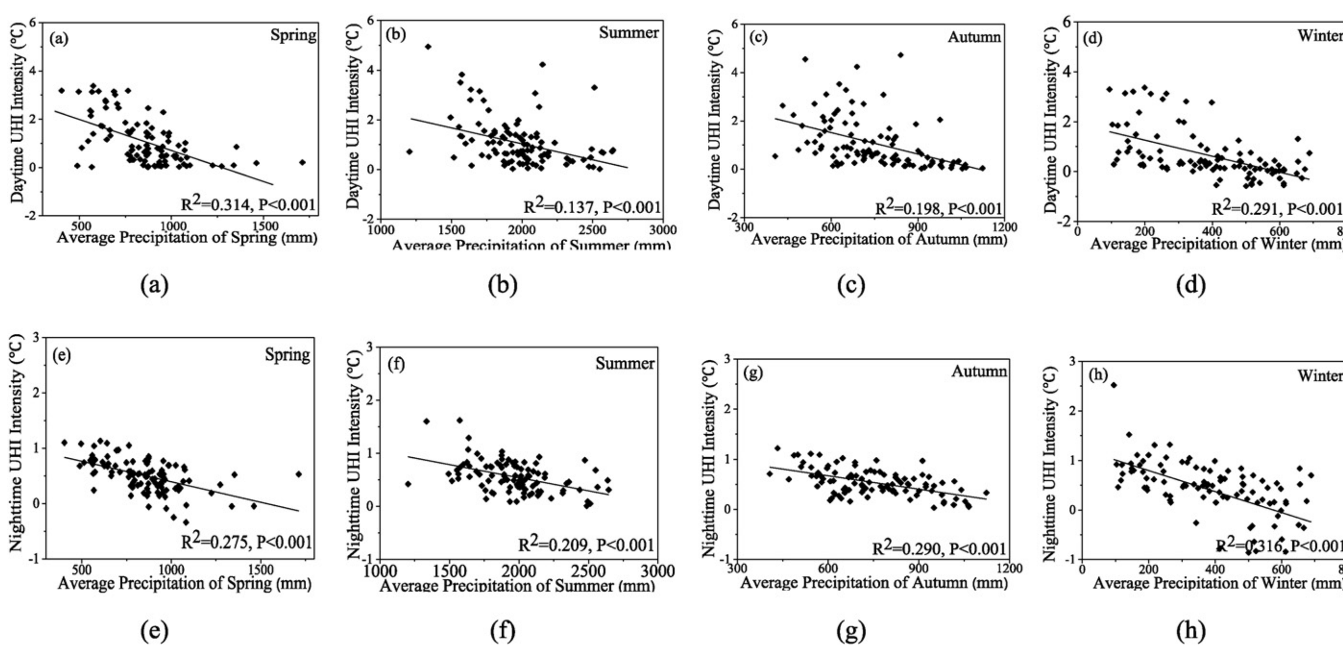

Fig. 8. (a)–(h) Correlations between average UHI intensity and average precipitation.

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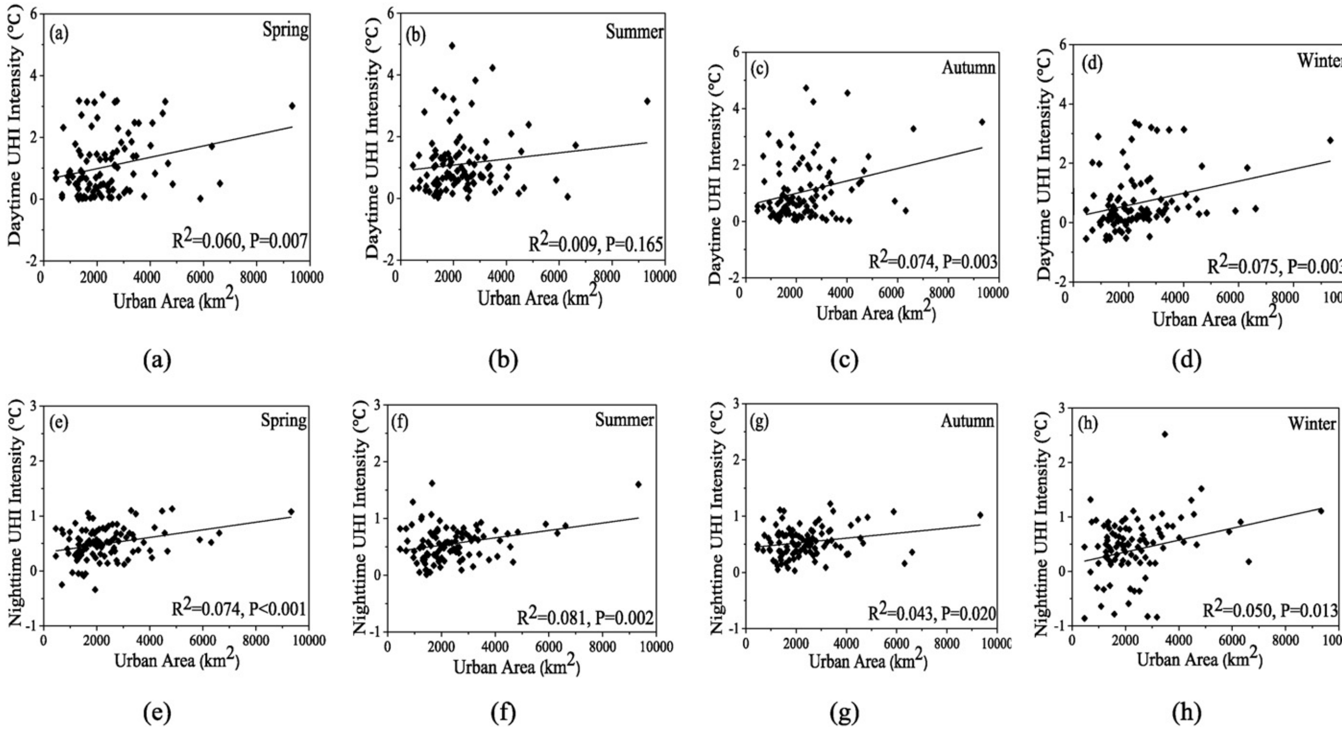

Fig. 9. (a)–(h) Correlations between average UHI intensity and urban area.

different seasons. The results expanded the spatial and temporal study scales of UHIs.

Appendix A. List of cities and counties in the YRDUA

Detailed information about the cities in the Yangtze River delta.

Appendix B. List of abbreviations

Yangtze River Delta Urban Agglomeration (YRDUA)
Yangtze River Delta (YRD)
Urban heat island (UHI)
Land cover types (LCT)
Standard deviation (STDEV)

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