Changing Characteristics of Urban Heat Island Effect in Weihai City

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Abstract Based on the local climate zoning theory and the observation data of hourly temperature of 22 automatic weather stations from 2012 to 2021, K-means clustering algorithm was used to analyze the daily, monthly, seasonal, annual and spatial variation characteristics of urban heat island effect in Weihai City in the past 10 years. The results showed that in recent 10 years, the average urban heat island intensity was 1.24 ℃, showing a gradual weakening trend of −0.169 3 ℃/10 a; the summer average heat island intensity was 0.86 ℃, showing a gradual weakening trend of −0.047 5 ℃/10 a. The heat island intensity had obvious diurnal variation characteristics, that is, "it was weak in the day and strong at night". In terms of seasonal variation, heat island effect was the weakest in summer, stronger in spring and autumn, and the strongest in winter. The diurnal, seasonal and annual changes of heat island intensity showed a reverse trend to those of temperature. The high-value area of urban heat island was highly consistent with human residential activity areas and industrial and commercial intensive areas, and the extension trend of heat island intensity was the same as the direction of urban development and construction. The "cold island phenomenon" in some offshore areas was related to the geographical location, terrain and the southeast monsoon trend in summer. The adverse effects of urban heat island effect can be reduced by optimizing the types and distribution of vegetation communities, rationally planning and constructing urban water body, promoting green building materials and adjusting shape design, *etc.*

Key words Urban heat island effect; Local climate zoning; K-means clustering algorithm; Automatic weather station

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With global warming and the acceleration of urbanization, urban heat island effect has gradually become one of the core factors affecting urban ecological environment. Due to changes in local climate conditions, the nature of urban underlying surface and man-made heat sources, a large amount of heat is collected in the urban space[1], and on the isotherm diagram of the near-surface atmosphere, the outline is like an island protruding from the sea level, so it is vividly called "urban heat island". Urban heat island collects air pollutants produced by residents' production and living to the city center, which will not only lead to the imbalance of urban ecological environment, but also increase energy consumption, resulting in poor residential comfort, and seriously affecting the daily life and health of residents.

In the *Climate of London* published in 1818, meteorologist Luke Howard first pointed out that there was a significant temperature difference between the urban and suburban areas of London. Since then, domestic and foreign scholars have used a variety of methods to carry out a large number of observations and theoretical studies on the heat island effect of different cities. For instance, based on the meteorological data from 1901 to 1984 of the American Historical Climate Network, Karl *et al.* found that urbanization increased the average urban temperature by about 0.06 ℃[2]. After studying relevant meteorological data in North America, Kukla *et al.* found that urbanization had an impact of 0.12 ℃/10 a on the average urban temperature[3]. In the 1980s, Zhou Shuzhen *et al.*[4] summarized the changing law of heat island effect in Shanghai based on the observation data of temperature in Shanghai, so as to lay a foundation for the study of domestic urban heat island effect. In this paper, based on the hourly temperature observation data of automatic stations in Weihai from 2012 to 2021, the optimized weather station data method was used to analyze the daily, monthly, seasonal and annual variation characteristics of urban heat island effect in Weihai City from two dimensions of time and space, and corresponding measures to mitigate the development of urban heat island effect were proposed to provide theoretical reference for urban planning and construction, energy structure, and sanitation and health research.

1 Data and methods

1.1 Study area Weihai is located in the easternmost end of Shandong Peninsula (36°41′ – 37°35′ N, 121°11′ – 122°42′ E), and precisely located on the north – south bisector of China. It is surrounded by the sea on three sides, and has China's longest coastline. It is opposite the Liaodong Peninsula and the Korean Peninsula across the sea, connects with land on one side, and borders Yantai City in the west. It has a monsoon continental climate, with four distinct seasons, and the monsoons advance and retreat markedly. The study area includes the main urban area of Weihai City (Huicui District) and its surrounding suburbs (Wen-

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deng District, Rongcheng City and Rushan City), with a length of 81 km from north to south, a width of 135 km from east to west, and a total area of 5 799.84 km^2.

1.2 Research data The hourly temperature observation data of 65 automatic weather stations in the study area from 2012 to 2021 were selected for data quality control and evaluation through the meteorological data operations system (MDOS) of China Meteorological Administration. In order to reduce the loss of valid data, the observation data without MDOS quality control was identified by manual operation according to the meteorological industry standard *Quality Control of Meteorological Observation Data—Surface* (QX/T 118 – 2020). Due to problems such as site maintenance and data transmission, the original data is partially missing. Year and sites with a missing test rate of less than 1% were selected. Then, in the data pre-processing stage, sklearn's imputer method was used to replace the missing test values with the mean of feature columns. Finally, the hourly temperature observation data of 22 automatic weather stations from 2012 to 2021 in the study area were selected. The relevant social and economic data was from the *Statistical Yearbook of Weihai City* in the corresponding years.

1.3 Research methods

1.3.1 Comparison of methods. There are many methods to study urban heat island effect, including satellite remote sensing, numerical simulation and meteorological data. The method of indirectly characterizing urban air temperature by retrieving land surface temperature based on remote sensing data has the advantages of simple data acquisition, wide monitoring range and strong time series. Surface temperature is closely related to air temperature, but due to the interference of cloud cover, underlying surface, buildings and other conditions, it is easy to generate bias when air temperature is reversed from surface temperature, resulting in low inversion accuracy. Moreover, the temporal resolution and spatial resolution of remote sensing data cannot meet the accuracy requirements at the same time, and cannot be used for the refined study of long-term urban heat island effect.

The numerical simulation method means that based on thermodynamics and dynamics theory, statistical, numerical, analytical and physical models are established by meteorological simulation software to simulate and predict urban heat island effect under spatiotemporal changes. It has the advantage of high spatial resolution, reveals the three-dimensional characteristics of heat island circulation, show the evolution mechanism and formation mechanism of heat island effect from the perspective of time and space, and is widely used in the research of the causes of urban heat island effect and mitigation measures. However, because of the numerous factors affecting urban heat island, the large environmental differences between cities, the complex diversity of underlying surfaces and the incomplete data system, the universality of numerical simulation is limited. In addition, this method also needs a lot of measured meteorological data, so it is usually suitable for the study of small-scale blocks or buildings.

The weather station data method means that urban heat island intensity can be calculated through the temperature data continuously observed by weather stations, directly and quantitatively reflecting the characteristics and changes of urban heat island effect, and the data is real and reliable. However, due to the limitation of the number, density and integrity of data series of stations, and the continuous change of urban underlying surface type and local climate, the accurate selection of urban and suburban stations is the key factor restricting the weather station data method. Taking into account factors such as land cover, spatial form, building materials and human activities, supplemented by remote sensing images, Stewart *et al.* proposed LCZ (local climate zone) theory in 2012 to screen out units that can represent urban and suburban areas[5], but it was susceptible to interference by meteorological factors.

1.3.2 Optimized weather station data method. The selection of urban sand suburban stations should meet the following requirements: they should have a suitable distance, difference in population density, generally consistent regional climate change, the same data length of stations, and small changes in the surrounding environment in the study period, and the temperature difference between urban and suburban stations can be clearly reflected.

From 65 automatic weather stations in the urban sand suburban stations of Weihai City, combined with the urban construction layout of Weihai (Fig. 1a), 22 stations were initially selected according to the LCZ theory and factors such as underlying surface type, data accuracy rate and establishment time of weather stations, and they were classified by K-means clustering analysis algorithm. The results are as follows: 10 stations belonged to class Ⅰ, all of which were distributed in urban areas, with an annual average temperature of about 13.41 ℃, and they were as representative stations of urban areas. Class II and Class III both consisted of 6 stations, with an annual average temperature of about 12.05 ℃, and they were as representative stations of suburban areas. The screening results and geographical locations are shown in Table 1 and Fig. 1b.

Table 1 Screening results of representative stations of automatic weather stations in urban and suburban areas of Weihai

Screening areas (number of stations)	Screening conditions	Areas	Screening results (number of stations)
Huancui District (19)	Population of the suburban transition area	Urban areas	10
Wendeng District (11) Rongcheng City (21) Rushan City (14)	Local climate change, and integrity of data sequence	Suburban areas	12
Total (65)			22

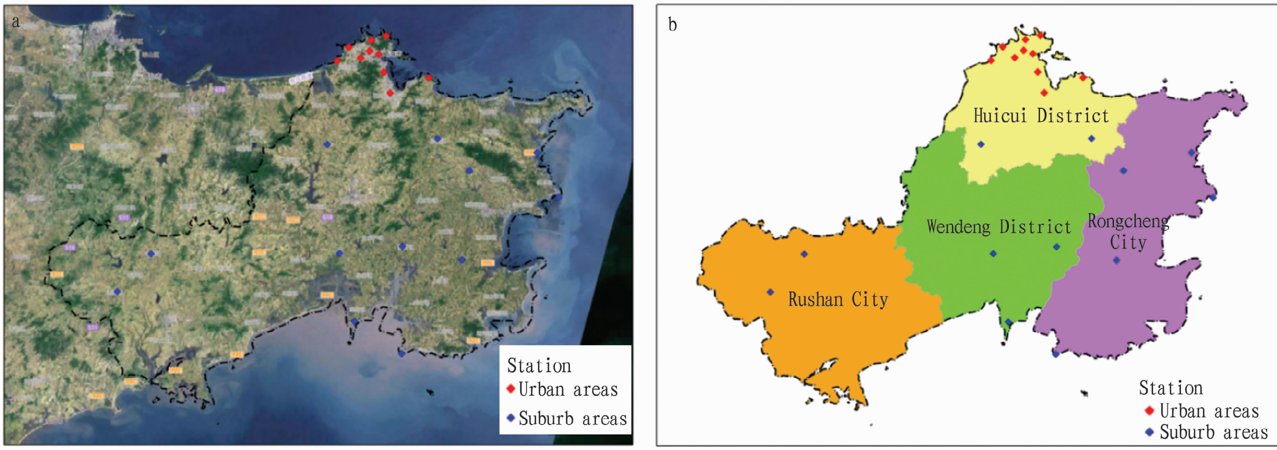

Fig. 1 Built-up area (a) and distribution of automatic weather stations in urban and suburban areas (b) in Weihai City

The daily, monthly, seasonal and annual variations of urban heat island effect in Weihai were analyzed by linear trend analysis. Among them, the process of K-means clustering analysis algorithm is as follows: the mean square error was used as the standard measure function, and k objects were randomly selected from the set containing n experimental objects as the initial clustering centers, and the remaining $n-k$ experimental objects were compared with these initial clustering centers; according to the degree of similarity, they were reorganized to obtain the new clustering centers; the mean was obtained by arithmetic average and as the new clustering center; it was iterated until the mean square error converged. The obtained k clusters were made as compact as possible, and the clusters were separated as far as possible. The standard measure function is defined as follows:

$$E = \sum_{i=1}^{k} \sum_{p \in C_i} |p - m_i|^2 \quad (1)$$

In the formula, the mean p of the cluster represents a point in the space, and E represents the sum of the mean square deviations of all objects. p and m_i are both multidimensional.

The heat island intensity was calculated by the difference between the average temperature of the selected urban and suburban stations:

$$I_{UHI} = \frac{1}{m}\sum_{i=1}^{m} T_i - \frac{1}{n}\sum_{j=1}^{n} T_j \quad (2)$$

In the formula, T_i is the temperature of m urban meteorological stations, $i = 1, 2, \cdots, m$; T_j is the temperature of n suburban meteorological stations, $j = 1, 2, \cdots, n$.

2 Results and analysis

2.1 Annual changes

2.1.1 Changes of average temperature in urban and suburban areas of Weihai in recent 10 years. Fig. 2 shows the changes of average temperature in urban and suburban areas of Weihai in recent 10 years. The mean temperature was obtained from the arithmetic average of observation data of 24-h hourly temperature. The urban temperature showed a rising trend of 1.475 2 ℃/10 a, and the suburban temperature had an increasing trend of 1.644 4 ℃/10 a. The rising trends were obvious, both passing the significance test at 0.05 level. All of them were higher than the growth rate of annual average temperature of 0.26 ℃/10 a in China and the global average temperature of 0.15 ℃/10 a since 1951. The temperature in the suburbs was always lower than that in the urban areas, indicating that Weihai City had a relatively obvious urban heat island effect.

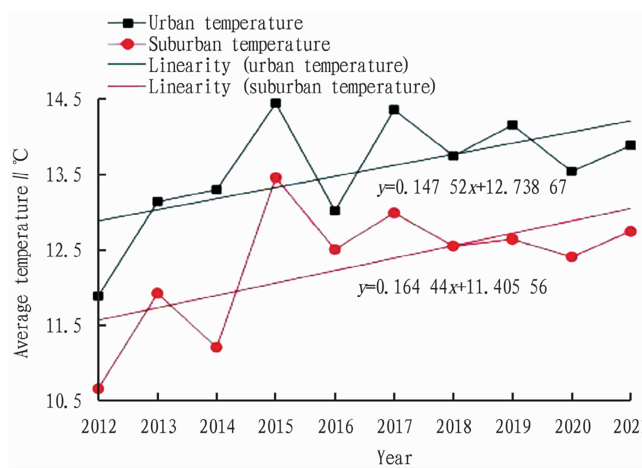

Fig. 2 Evolution of average temperature in urban and suburban areas of Weihai City in recent 10 years

2.1.2 Changes of urban heat island intensity in Weihai City in recent 10 years. Although the annual average temperature in the urban and suburban areas of Weihai increased rapidly in recent 10 years, the average heat island intensity showed a gradually decreasing trend (Fig. 3). The annual mean heat island intensity was the strongest in 2014, up to 2.1 ℃. It was the weakest in 2016, only 0.5 ℃. It fluctuated from 1.0 to 1.5 ℃ in the rest of the year. In recent 10 years, the average heat island intensity was 1.24 ℃, and the changing trend rate of the average heat island intensity was -0.169 3 ℃/10 a, showing a gradual slowing trend and passing the significance test at 0.05 level. This is related to environmental protection measures such as the continuous relocation of large-scale industries from the main urban area to the suburbs and the emphasis on urban green construction in Weihai City in recent years. In addition to the change of urban underlying surface type, urban heat island effect is also affected by urban economic and social development and human activities. According to

Table 2, the growth rate of retail sales of consumer goods and gross domestic product in Weihai City was positively correlated with the annual average heat island intensity, and negatively correlated with the annual average temperature in the urban and suburban areas. It can be seen that the traffic flow, people flow, logistics and various industrial and commercial activities, which directly affected the retail sales of social consumer goods in the city, as well as the growth rate of GDP were important influencing factors of urban heat island effect.

As shown in Fig. 3, the inter-annual evolution of the annual average heat island intensity in summer (from June to August) was consistent with that of the annual average heat island intensity, and both showing a slow weakening trend. The changing trend rate was −0.047 5 ℃/10 a, passing the significance test at 0.05 level. The average heat island intensity in summer was 0.86 ℃, with a range of 0.7 − 1.1 ℃. As can be seen from Table 2, summer heat island intensity was positively correlated with economic and social indicators, and the correlation was strong, possibly because summer is the peak season of tourist in Weihai.

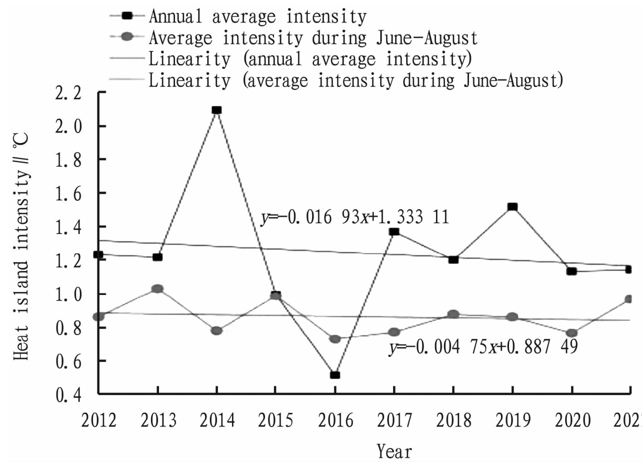

Fig. 3 Changing trend of annual and summer average heat island intensity in Weihai City in recent 10 years

Table 2 Correlation of urban heat island effect and related economic indicators in Weihai

Urban economic indicators	Urban temperature		Suburban temperature		Annual average heat island intensity		Average heat island intensity during June – August	
	Correlation coefficient	*P* value	Correlation coefficient	*P* value	Correlation coefficient	*P* value	Correlation coefficient	*P* value
Growth rate of GDP	−0.356 6	0.003 6	−0.352 4	0.003 5	0.403 4	0.003 4	0.384 5	0.003 1
Growth rate of retail sales of consumer goods	−0.163 3	0.013 7	−0.106 0	0.013 9	0.513 9	0.013 9	0.572 6	0.009 4

Note: *P* value is the *P* value of hypothesis test.

2.2 Seasonal variation As shown in Fig. 4, the urban heat island effect in Weihai in recent 10 years was the weakest in summer (June – August), and the intensity was as low as 0.86 ℃. It was stronger in spring (March – May) and autumn (Septemst – November), and the intensity was 1.32 ℃. It was the strongest in winter (Decemb – next February), up to 1.38 ℃. It was consistent with the seasonal variation characteristics of urban heat island intensity in most cities. The heat island effect in Beijing City was also the strongest in winter[6], which is consistent with the conclusion of this study. In summer, rainfall increases, and vegetation coverage is high. Water evaporation and vegetation transpiration take away a lot of heat from the environment, which not only reduces air temperature and increases air humidity, but also absorbs a lot of carbon dioxide and inhibits the greenhouse effect. Compared with summer, in autumn and winter, due to the influence of cold air mass, buildings and streets form a relatively closed environment, so the suburban circulation is weakened, and the radiation inversion layer is thicker, which is not conducive to urban heat dissipation. As a result, the temperature difference between urban and suburban areas increases, and the heat island effect is enhanced. Besides, in autumn and winter, the amount of heating discharged heat and pollutants in urban areas will be more than these in the suburbs, the temperature difference in urban and suburban areas further increases. Mao Chengzhong *et al.* [7] analyzed the urban heat island of Yichang, and pointed out that the heat island effect of Yichang was stronger in summer and autumn. Walijiang *et al.* [8] analyzed the heat island intensity of Urumqi, and found that it was strongest in autumn, but it was also stronger in winter. It can be seen that urban heat island effect is strong in autumn and winter and weak in summer, which is the general law of urban heat island effect changing with the seasons, but it can not be simply considered that every city conforms to this law, and the reasons for the differences should be analyzed according to the population of the study area, the density of the underlying surface, and the situation of central heating in winter.

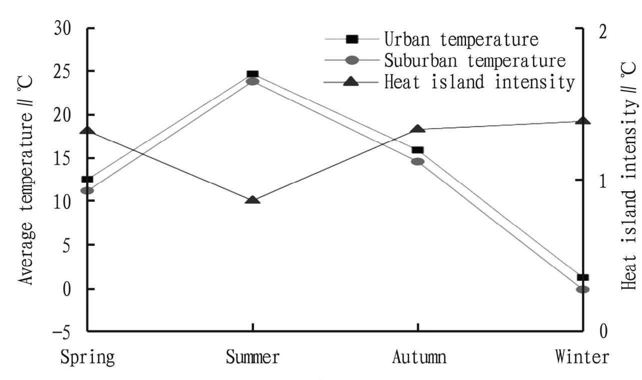

Fig. 4 Seasonal variation of heat island effect in Weihai in recent ten years

From Fig. 5, it can be seen that from early spring to late spring, the heat island intensity in Weihai City rose first, then decreased, and finally increased to 1.48 ℃, experiencing a reciprocating stage. In early summer, midsummer and late summer, the heat island intensity dropped to the annual valley of 0.66 ℃, and then rose to the peak of 1.64 ℃ from early autumn to early winter, while it continuously decreased to 1.03 ℃ in mid-winter and late winter. On the whole, heat island intensity was negatively correlated with temperature, and their changes were basically synchronous.

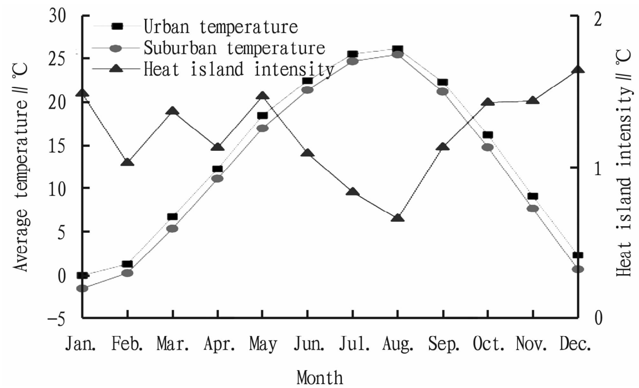

Fig. 5 Monthly variation of heat island intensity and temperature in urban and suburban areas of Weihai in recent 10 years

2.3 Monthly variation As shown in Fig. 5, the temperature of Weihai City reached its annual peak in August, up to 26.12 and 25.47 ℃ in the urban and suburban areas, respectively. In January, temperature was the lowest in the whole year, only −0.02 and −1.50 ℃ in the urban and suburban areas, respectively. The changing curve showed a symmetrical distribution with August as the symmetry axis. Heat island intensity reached the highest point in December, up to 1.64 ℃. It gradually decreased to 1.03 ℃ from January to February, and increased to 1.46 ℃ from March to May. It continuously declined to the annual valley of 0.66 ℃ from August, and then continued to rise to 1.64 ℃ in December. It can be seen that from January to April, heat island intensity presented a "broken line" fluctuating up and down, with a range of 1.03 − 1.48 ℃. However, from August to December, heat island intensity continued to rise without a "broken line", which is consistent with the result of seasonal variation that heat island intensity was stronger in autumn and winter and the weakest in summer. The thermal hysteresis effect caused by the difference in thermal properties of urban and suburban underlying surface led to this obvious "reverse phase" phenomenon. That is, temperature increase in the urban areas lagged behind that of the suburbs, resulting in a relatively small temperature difference between the urban and suburban areas, and the urban heat island effect was weakened. Temperature dropped faster in the urban areas than in the suburbs, so that the temperature difference between the urban and suburban areas became relatively larger, and the urban heat island effect was enhanced.

2.4 Diurnal variation The hourly average temperature and urban heat island intensity in Weihai City from 2012 to 2021 are shown in Fig. 6. The diurnal variations of temperature in the urban and suburban areas was the same. The maximums appeared at 13:00, up to 15.56 and 15.58 ℃. The minimums can be found at 05:00, only 11.1 and 8.9 ℃. Heat island intensity was relatively stable at night, and reached the highest point of the day. It gradually weakened in the morning, and dropped to the lowest value at noon. Then it slowly increased, and gradually stabilized at night. It can be seen that heat island intensity had obvious diurnal variation characteristics, that is, " it was weak in the day and strong at night", and it was also "antiphase", which is consistent with the conclusions of previous studies[4, 8-9]. There were three reasons for the diurnal variation of urban heat island effect. The first reason was the difference in heat storage between the urban and suburban areas, that is, the thermal difference between urban and suburban underlying surfaces and the large amount of heat emitted by artificial heat sources resulted in more heat stored in the urban areas than in the suburban areas. The second one was the difference of insulation capacity between the urban and suburban areas. Compared with the suburbs, the content of greenhouse gases in the urban atmosphere was higher, and the reverse radiation was stronger; it is easy to absorb more long-wave radiation, and the heat preservation effect was obvious. The third one was the difference of reflectivity between the urban and suburban areas. Urban buildings are uneven and scattered, and the "sky visibility" was lower than the suburbs, so heat is difficult to disperse, and the suburban reflectivity was about 10% −15% larger than the urban areas.

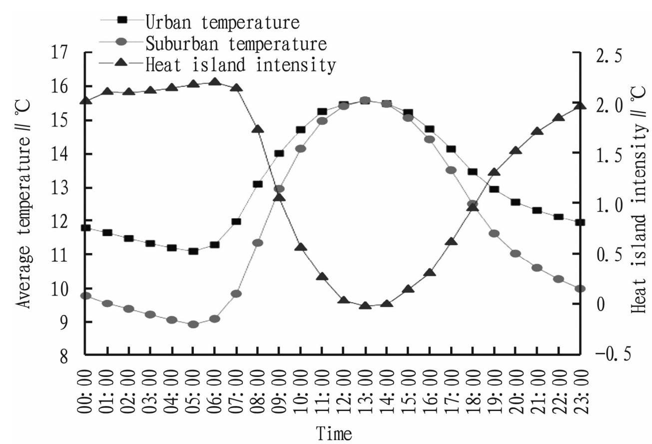

Fig. 6 Diurnal variation of heat island intensity and average temperature in urban and suburban areas of Weihai in recent 10 years

2.5 Spatial distribution

2.5.1 Annual average heat island effect. Fig. 7a shows the spatial distribution of mean temperature in Weihai City in recent 10 years. Huanchui District in the north is the core area of the city, with dense buildings, dense population and developed commerce. Rongcheng City in the east, as one of the top 100 counties in China, gathers a large number of tourist attractions and docks in the northeast corner. The population, industrial and commercial density of Wendeng District in the central-south and Rushan City in the west are far smaller than the above two regions. It can be obviously seen that high-temperature areas were mainly concentrated in the coastal areas, and bordered Weihai in the west, where temperature was obviously higher than the inner suburbs. Temperature gradually decreased from the edge of the city to the center, and the overall distribution was approximately "O" shaped, corresponding to the fact that Weihai City is surrounded by the sea in the north, east and south and bordered by the inland in the west, and the economically developed areas are mainly concentrated near the coastal areas. Rushan City borders Yantai City in the west, with sparse population and less industry and commerce, but temperature is high. It can be seen that the ocean plays a significant role in reducing the temperature of the city. It can be clearly seen from Fig. 7b that heat island intensity was stronger in the urban areas than in the suburban areas, and it was higher in the coastal areas than in the inland areas. The high-value area of heat island intensity was located in Huichui District in the central urban area of Weihai City, which is basically consistent with the change of temperature distribution.

2.5.2 Heat island effect in summer. The average heat island intensity in summer and the annual average heat island intensity in Weihai City were quite different. The difference is mainly shown as follows: the summer average temperature and heat island intensity of Rongcheng City were relatively low, which was closely related to the geographical location of Rongcheng City in the east coast and the southeast monsoon in summer. There were low-temperature patches in Wawushi Village (Fig. 7c), and there were three low-lying areas of summer average heat island intensity extending to the northeast (Fig. 7d). It is consistent with the fact that the three areas are peninsula types, with flat and narrow terrain and significant southeast monsoon in summer, which is also one of the reasons why the urban heat island effect in Weihai was the weakest in summer.

2.5.3 Heat island intensity in recent five years. Fig. 7e and Fig. 7f show the spatial distribution of urban heat island intensity in Weihai in 2016 and 2021. There was a heat island patch in the urban areas, with an increase of about 2.55 ℃, but the heat island intensity of the urban representative station (Weihai station) decreased by 0.05 ℃, and the urban heat island intensity in recent 5 years only increased by 0.15 ℃. As shown in Table 3, the population growth was about 0.24%, indicating that the city size had reached a stable state. The electricity consumption of the whole society, natural gas consumption, the number of public transport vehicles, and the area of garden green space increased by 40.02%, 138.16%, 31.97%, and 55.70%, respectively, while heat island intensity decreased by 3.85%. It shows that the promotion and use of clean energy, the development of public transportation and the continuous increase of urban green body can effectively inhibit the enhancement of urban heat island effect. In addition, the intensification trend of urban heat island intensity in recent five years extended eastward and southward from the main urban areas, which was consistent with Weihai municipal government's emphasis on the development of Binhai New City, Lingang District and Nanhai New Area in recent years.

Table 3 Comparison of some socio-economic data and heat island intensity in Weihai City in 2016 and 2021

Year	Population // 10^4	Electricity consumption 10^8 kW · h	Natural gas consumption // 10^4 m^3	Number of public transport vehicles in operation	Area of garden green space // hm^2	Heat island intensity of Represents the representative station // ℃
2016	255.86	108.7	13 546.50	1 639	9 121	1.30
2021	256.47	152.2	32 261.81	2 163	14 201	1.25
Growth // %	0.24	40.02	138.16	31.97	55.70	-3.85

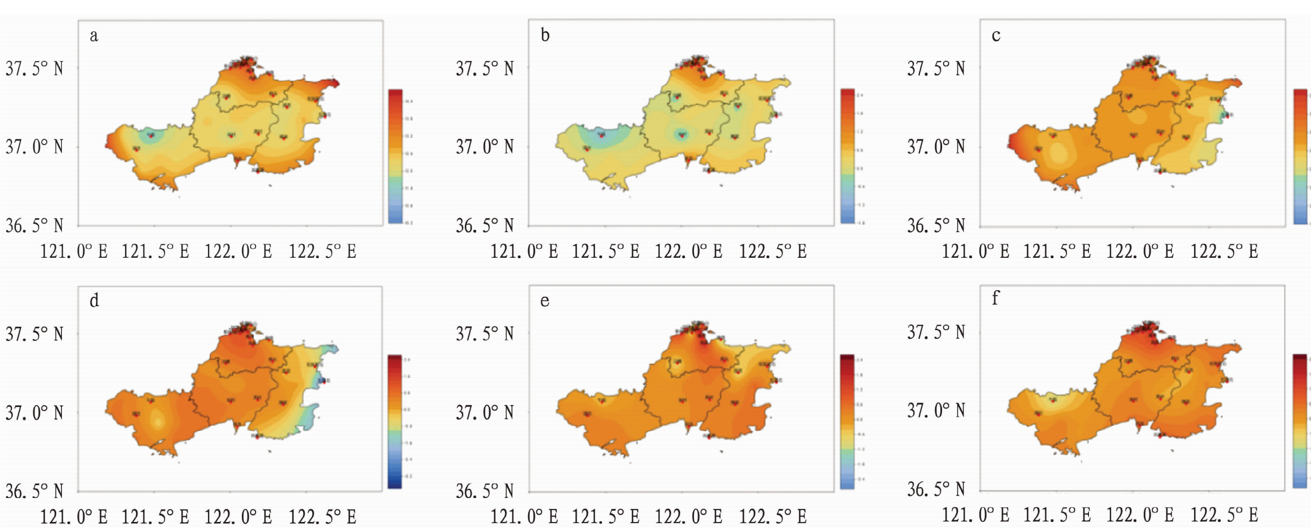

Fig. 7 Average temperature (a), average heat island intensity (b), average temperature from June to August (c), and average heat island intensity (d) in recent 10 years as well as heat island intensity in 2016 (e) and 2021 (f) (unit: ℃)

3 Mitigation strategies

Generally speaking, the areas with increased heat island intensity are mainly concentrated in three areas: Yuanyao Qianhai Science and Technology Bay Area, Haoyunjiao Tourist Resort Area and Lingang Economic and Technological Development Zone. As the original green vegetation and water body are gradually replaced by a large number of buildings and streets, most of the supporting greening and water body are not yet perfect, so urban heat island effect is significant. Based on the above general situation of urban development and the specific geological landform, water network and limited water and soil resources of the city, mitigation strategies for urban heat island effect in Weihai are formulated, such as optimizing the types and distribution of vegetation communities, rationally planning and constructing urban water body, promoting green building materials and adjusting the shape design to reduce the adverse effects of urban heat island effect.

3.1 Adjusting and determining urban land planning and layout Land planning and layout based on rational urban land cover properties is the core of restraining urban heat island effect. The solar altitude and wind direction in a city are different in different seasons of the year and at different times of a day, and environmental factors are constantly changing. Besides, the structure of the external walls and roofs of buildings, as well as the layout of streets, also have a crucial impact on the reflection of solar energy and the direction of wind. Therefore, under the specific resources and environment of the city, it is necessary to adjust the urban land planning and layout, determine the proportion of land use, increase the construction of urban green space and wetlands, improve the thermal properties of urban underlying surface, increase the absorption rate of solar radiation, optimize the green space, blocks, roads and building structures, and promote the construction of green breeze passage on the sea (introducing water vapor and sea breeze from the Yellow Sea into the urban areas of Weihai), which has a good effect on the improvement of urban heat island effect.

When the construction pattern is basically formed and land resources are limited, the most direct way to weaken the urban heat island effect is to increase the urban green space coverage. In addition, compared with pure grassland, shrub grassland and arboreal grassland have better cooling and humidification effect[10]. Besides, it is also necessary to combine the needs of urban planning and construction to layout the appropriate green space and select the best vegetation type.

3.2 Giving play to the cooling effect of urban water body To promote the construction of urban diversified ecological civilization, it is needed to pay more attention to the role of water body and future newly-increased water body in improving urban local microclimate and alleviating urban heat island effect. As an urban cold island, urban water body transports energy outward in the form of latent heat because of its large heat capacity and good heat conductivity, which can significantly reduce the temperature in the space range. However, due to the limited area of urban water body, the intensity of cold island effect cannot be enhanced by unrestricted increase of water body area, and the efficiency of cold island decreases gradually with the increase of water body area. Therefore, based on urban planning and layout, factors such as the area, spatial layout and shape index of urban water body as well as coverage characteristics of buffer zones should be fully considered[11]. Peng *et al.* found that the spatial heterogeneity of cold island intensity of urban water body was obvious; the factor that had the greatest impact on it was water body area, and it was significantly negatively correlated with the surrounding surface temperature of water body[12]. Sun *et al.* analyzed the factors affecting the cold island effect of urban water body in Beijing, and found that the larger the water body, the stronger the cold island effect, but with the increase of water body area, the cold island efficiency of water body declined gradually[13]. Moreover, Tan *et al.* found that the more complex the shape of water body, the larger the area affected by the cold island effect, and the cold island intensity of the city was positively correlated with the shape index of wetland landscape[14]. In terms of water body layout, Sun *et al.* found that multiple small waters had stronger cold island intensity than larger waters with the same area and smaller number[15]. Through numerical simulation of water body in residential areas, Hong *et al.* found that widely distributed discrete water body had stronger cold island effect than concentrated water body[16].

3.3 Improving urban building materials and developing three-dimensional greening During the reconstruction of the old city and the construction of a new district, the roof and facade of a building should be made of light-colored surface paving materials with high reflectivity and low thermal inertia, which can accelerate the conduction of heat and reduce the absorption of solar radiation. It is needed to eliminate the traditional non-permeable ground, promote the ecological pavement pavement materials that have functions of water permeation, storage, and purification, repair the urban water circulation system, and reduce the pavement temperature through the transpiration of groundwater, which has a positive significance to mitigate heat island effect.

The development of three-dimensional greening, the introduction of scientific green roof design scheme and the building exterior wall climbing and hanging vine green plants and other measures can solve the pain points of traditional greening without land, can effectively reduce the building temperature and adjust the local microclimate in the urban center.

4 Conclusions and discussion

(1) The urban average heat island intensity in Weihai from 2012 to 2021 was 1.24 ℃, and the climate tendency rate was −0.169 3 ℃/10 a. The summer average heat island intensity was 0.86 ℃, and the climate tendency rate was −0.047 5 ℃/10 a. That is, it showed a slow decreasing trend, and the climate tendency rate passed the significance test at 0.05 level. In recent 10 years, the growth rate of retail sales of social consumer goods and urban gross domestic product in Weihai had a positive correlation with the average heat island intensity, indicating that the traffic flow, people flow, logistics and various industrial and commercial activities directly affecting the total retail sales of urban consumer goods, as well as the growth rate of GDP were important influencing factors of the urban heat island effect.

(2) The diurnal variation trend of urban heat island intensity in Weihai is as follows: it reached the highest point in the day at night, slowly weakened in the morning, reached the lowest point at noon, then gradually increased to the highest point, and remained stable at night. In a word, the urban heat island intensity in Weihai had obvious diurnal variation, that is, " it was weak in the day and strong at night".

(3) In the monthly variation of heat island intensity in Weihai, it reached the highest point (up to 1.64 ℃) in December, gradually decreased to 1.03 ℃ from January to February, rose to 1.46 ℃ from March to May, then continuously decreased to the annual valley value of 0.66 ℃ from August to August, and finally continuously increased to 1.64 ℃ in December. In terms of seasonal variation, urban heat island intensity was the weakest in summer (as low as 0.86 ℃), stronger in spring and autumn (both up to 1.32 ℃), and the strongest in winter (1.38 ℃), which accords with the general law of seasonal variation of urban heat island intensity. This is inconsistent with the seasonal variation of urban heat island intensity in southern China, which may be related to central heating in winter in northern China.

(4) Seen from the diurnal, monthly, seasonal and annual variations of urban heat island intensity in Weihai, it was the strongest when temperature was the lowest, and the weakest when temperature was the highest, showing an obvious "inverse phase" with the temperature change. This is due to the "thermal hysteresis effect" caused by the significantly higher thermal conductivity and heat capacity of the underlying surface in the urban areas than that in the suburban areas.

(5) The high-value area of urban heat island intensity in Weihai was highly consistent with human residential activity areas and industrial and commercial intensive areas, and the extension trend of heat island intensity was also the same as the direction of urban development and construction. The "cold island phenomenon" in some offshore areas may be related to the geographical location, terrain and the southeast monsoon in summer.

(6) Based on the specific geological landform, water network and limited water and soil resources of Weihai City, urban heat island effect can be alleviated by optimizing the types and distribution of vegetation communities, rationally planning and constructing urban water bodies, promoting green building materials and adjusting the shape design.

The optimized weather station data method was used to analyze the spatial and temporal variation characteristics of heat island effect in Weihai City, and the length of data series and the number of observation stations were taken into account. The quantitative results are intuitive, and the evaluation conclusions are objective, which are easy to be accepted by the public and decision-making services. However, it is still necessary to strengthen research on the fine distinction between urban and suburban weather stations, quality control and screening of data, how to integrate weather station data method, remote sensing inversion and numerical simulation, and how to carry out multi-dimensional and deep comprehensive expansion and extension from unilateral study of urban heat island effect to urban thermal environment, heat island circulation and heat island formation mechanism.

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(From page 7)

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