Contributions of sea–land breeze and local climate zones to daytime and nighttime heat island intensity

Jun Yang1,2,6, Jiaxing Xin1, Yuqing Zhang1,5, Xiangming Xiao3 and Jianhong Cecilia Xia6

The acceleration of global urbanization has increased the frequency of the urban heat island (UHI) effect and heatwaves, which seriously endanger human health. We used Shenzhen as a case study to examine the daytime and nighttime differences in UHI intensity (UHII), considering different local climate zones (LCZs) and sea–land breezes. The diurnal UHII was >3 °C for 52% of the study period, whereas the nocturnal UHII was >3 °C for only 26% of the study period. The average diurnal and nocturnal building-type UHII values were 2.77 and 1.11 °C higher than those of the natural type, respectively. Sea breezes alleviated the UHI effect with a linear correlation coefficient of −0.68601 between them. Moreover, diurnal and nocturnal UHII showed differences across different gradients, which can help guide urban planning.

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INTRODUCTION

Urbanization has been accelerating since the beginning of the 21st century1–3. In China, as the population increases annually4, the areas under impervious layers have also witnessed increases, causing surface temperatures to increase and exacerbate the urban heat island (UHI) effect, extreme weather, and heat waves5–8, all of which affect human comfort and threaten human health9–13, and even cause death. The UHI phenomenon was first discovered by Howard14, who conducted temperature observations in London, UK, and urban thermal environments have been the subject of active research ever since.

Surface temperature is an important parameter for urban thermal environment research15; therefore, many international studies have investigated methods to determine it. Compared with traditional meteorological station observations, thermal infrared (TIR) image data can retrieve land surface temperature more effectively. Owing to the advantages of this method, such as its spatial continuity and easily accessible images, it has been widely used in research on UHIs16–22. Depending on the source of the image sensor, TIR images can include high, medium, and low spatial resolution data, such as Landsat/TIRS (100 m), ASTER (90 m), GFS/VIMS (40 m), HJ-1B/IRS (300 m), and MODIS (1000 m).

Presently, studies on urban thermal environments commonly use Landsat TM/TIRS or MODIS data for land surface temperature inversion and UHI intensity (UHII) calculations, resulting in the development of heat island mitigation strategies18,20,23–31. However, the former is difficult to acquire at night, whereas the latter has a low resolution and cannot accurately analyze thermal environments at the urban-block scale. Therefore, MODIS data are more suitable for large-scale research on regional thermal environments. ASTER data have a high spatial resolution and can provide suitable night images. These data have become the main source for daytime and nighttime UHI research, respectively; therefore, AST_08 data were used in this study to conduct land surface temperature inversion calculations.

UHIs are affected by many factors, including architecture, climate, and land map32–38. However, owing to rapid urbanization in China, available morphological and land-use data are inevitably unstandardized, difficult to obtain, or cannot be used for urban planning or environmental research. The local climate zone (LCZ) classification scheme constitutes a climate-related land cover classification system for urban structures, which was first proposed by Stewart et al.39,40. This classification scheme has been used worldwide as an international standard for climate-related research41–43 and is widely used in UHI research44–49. Presently, LCZ classification methods can primarily be divided into two types. The first uses the World City Database Portal Tool (WUDAPT)50–53, the software required for this method is free, and the data are easily obtainable, but its spatial resolution is low; thus, it is only suitable for large-scale research. The second method uses a geographic information system (GIS) to calculate building parameters and vegetation indicators to divide LCZs into smaller study units54–57. Although obtaining data for this method is more difficult, the classification results correspond well with the actual field conditions. Therefore, the second classification method was used herein and building and land-use data were combined to classify the LCZs.

Recent studies have shown that urban ventilation can improve urban thermal comfort and alleviate the UHI effect58–61. Sea and land breezes, representative of typical local winds in coastal cities and which alternate during days and nights, refer to the mesoscale circulations formed via the temperature difference between the ocean and land. As they frequently occur in coastal cities, previous research has attempted to address the interactions between sea and land breezes and UHIs62–65. For instance, Sangobanwo66 revealed that coastal cities are more susceptible to UHIs due to sea–land breezes and are generally more prone to extremely high temperatures than inland cities. Wang et al.67 used the Weather Research and Forecasting (WRF) model to simulate the sea–land breeze and thermal environment, further analyzing its effect on the UHI. Shen and Yuan68 used the large eddy simulation module in the WRF model to simulate five urban cases and one non-urban case. They analyzed the interactions between sea–land breezes and UHIs, and found that sea–land breeze circulation was stronger in urban areas; moreover, they revealed...
that UHIs were alleviated when the wind speed was high and sea breezes flooded city interior. Sea–land breezes can also significantly affect UHIs. However, most studies have only qualitatively analyzed the weakening effect of sea breeze on the strength of the heat island.Few studies analyze the correlation between sea and land wind speed and UHII. In addition, discussing the strength of the sea and land breeze and heat island under different gradients (distance from the coastline) is necessary. This has important implications for urban planning and a rational layout of the city. Therefore, in this study, the effects of sea–land breezes on the daytime and nighttime UHIs were analyzed under different gradients based on meteorological data.

The main purpose of this study was to explore the internal differences in the urban thermal environment of Shenzhen from the perspective of LCZs and sea–land breezes. The main objectives were to: (1) analyze the UHI day and night spatial
differences based on the land surface temperature directly calculated from AST_08 images, (2) analyze the influence of different LCZ types on the intensity of heat islands based on Oke’s classification standard for LCZs, and (3) analyze the influence of different LCZ types on the intensity of heat islands based on Oke’s classification standard for LCZs, and (3) analyze the daily variation in the UHII between typical and atypical sea and land breeze days based on weather station data, and investigate the influence of the sea and land wind speeds on the intensity of heat islands under different gradients using correlation analysis. This study can provide a reference for urban planning and for mitigating the UHI effect.

RESULTS
Daytime and nighttime UHII and LCZ spatial distributions
Overall, the daytime and nighttime UHII spatial distributions (Fig. 1) were highly consistent with the spatial distribution of the

| Table 1. The statistical results of different LCZs in different regions. |
| --- |
| Location LCZ types Proportion Location LCZ types Proportion |
| Bao’an District LCZ1 0.0005679 Longhua District LCZ1 0.0000686 |
| LCZ2 0.0010569 LCZ2 0.0003087 |
| LCZ3 0.0016498 LCZ3 0.0007032 |
| LCZ4 0.0106007 LCZ4 0.0027107 |
| LCZ5 0.2190609 LCZ5 0.1021162 |
| LCZ10 0.0002152 LCZ10 0.0002152 |
| LCZ1 0.0005679 Longhua District LCZ1 0.0000686 |
| LCZ2 0.0010569 LCZ2 0.0003087 |
| LCZ3 0.0016498 LCZ3 0.0007032 |
| LCZ4 0.0106007 LCZ4 0.0027107 |
| LCZ5 0.2190609 LCZ5 0.1021162 |
| LCZ10 0.0002152 LCZ10 0.0002152 |
| LCZ1 0.0005679 Longhua District LCZ1 0.0000686 |
| LCZ2 0.0010569 LCZ2 0.0003087 |
| LCZ3 0.0016498 LCZ3 0.0007032 |
| LCZ4 0.0106007 LCZ4 0.0027107 |
| LCZ5 0.2190609 LCZ5 0.1021162 |
| LCZ10 0.0002152 LCZ10 0.0002152 |
| LCZ1 0.0005679 Longhua District LCZ1 0.0000686 |
| LCZ2 0.0010569 LCZ2 0.0003087 |
| LCZ3 0.0016498 LCZ3 0.0007032 |
| LCZ4 0.0106007 LCZ4 0.0027107 |
| LCZ5 0.2190609 LCZ5 0.1021162 |
| LCZ10 0.0002152 LCZ10 0.0002152 |
| LCZ1 0.0005679 Longhua District LCZ1 0.0000686 |
| LCZ2 0.0010569 LCZ2 0.0003087 |
| LCZ3 0.0016498 LCZ3 0.0007032 |
| LCZ4 0.0106007 LCZ4 0.0027107 |
| LCZ5 0.2190609 LCZ5 0.1021162 |
| LCZ10 0.0002152 LCZ10 0.0002152 |
| LCZ1 0.0005679 Longhua District LCZ1 0.0000686 |
| LCZ2 0.0010569 LCZ2 0.0003087 |
| LCZ3 0.0016498 LCZ3 0.0007032 |
| LCZ4 0.0106007 LCZ4 0.0027107 |
| LCZ5 0.2190609 LCZ5 0.1021162 |
| LCZ10 0.0002152 LCZ10 0.0002152 |

| Table 2. Summary of UHII in each LCZ in Shenzhen. |
| --- |
| LCZ types Nighttime (°C) Daytime (°C) LCZ types Nighttime (°C) Daytime (°C) |
| LCZ1 1.48 1.95 LCZA −0.48 −5.31 |
| LCZ2 1.16 1.69 LCZB 0.30 −0.17 |
| LCZ3 0.75 3.01 LCZC −0.43 −0.31 |
| LCZ4 0.35 3.14 LCZE −0.80 0.71 |
| LCZ5 −0.84 −0.15 |
| LCZ6 0.21 1.10 |
| LCZ7 2.20 0.18 |
| LCZ8 1.46 1.49 |
| LCZ9 0.84 2.07 |
| LCZ10 −0.02 0.48 |
UHII values in each interval, ranging from $-1$ to $3$ °C, show that the proportion at night is greater than that during the day (28% (night) > 7% (day), 16% (night) > 6% (day), 11% (night) > 6% (day), and 13% (night) > 12% (day)).

**UHII variations by LCZ**

Table 2 lists the average daytime and nighttime UHII values corresponding to other LCZ types, except water bodies (LCZF). As AST_08 recorded the dynamic temperatures of the Earth’s land surface, water bodies were not analyzed. LCZ5 and LCZ6 exhibited the lowest nighttime and daytime UHII (−0.84 and −5.31, respectively), whereas the highest nighttime and daytime UHII were observed for LCZ7(2.20) and LCZ4(3.14), respectively. Figure 3 shows the differences in the daytime and nighttime UHII among the various LCZ types. The building types (LCZ1–LCZ10) generally exhibited higher UHII values, whereas the natural types (LCZA–LCZE) showed lower values. The average nighttime and daytime UHII values of the building types were 1.11 and 2.77 °C higher than those of the natural types, respectively. In addition, LCZ types with different vegetation coverage also exhibited differences in their daytime and nighttime UHII. During the daytime, LCZ types with high vegetation coverage (LCZ10, A, B, and C) exhibited lower UHII than LCZ types with low vegetation coverage (LCZ3, 4, and E). At night, the UHII values of LCZ7 and 8 were higher than those of LCZ1 and 2, which had lower levels of vegetation coverage. This is because the impervious surface of the city differs from the surfaces with vegetation, the reflectivity of solar radiation is small, the heat capacity is large, and the near-surface layer is relatively stable at night, resulting in poor heat dissipation, high stored heat, and a significant heat island effect.

**Influence of sea and land breeze on UHII**

Taking the offshore G3643 station as an example, typical (no significant changes in wind speed and direction) and atypical (diurnal changes in wind speed and direction) sea–land breeze days were analyzed, as shown in Fig. 4 (the typical sea–land breeze day was November 1, 2019, and the atypical sea–land breeze day was November 5, 2019). The results showed that the wind speed and direction were evidently disturbed by the onset of the sea breeze. The wind direction changed from offshore at the last moment to onshore, with an increase of >90°, and the wind speed increased rapidly. However, as the sea breeze developed, the wind direction stabilized. In the onshore wind direction, the wind speed reached its daytime maximum at ~14:00 (Beijing: GMT + 8). When the sea breeze ended, the wind direction suddenly shifted offshore, and the land breeze started developing. The wind speed reached its intraday maximum at ~03:00 at night (Beijing: GMT + 8). For atypical sea and land breeze days, the dominant wind direction was southeast, and the wind speed remained at 1 m·s⁻¹.

To compare the influence of the presence or absence of sea–land breeze on the intensity of heat islands, the daily variation characteristics of the heat island intensity on typical and atypical sea–land breeze days were analyzed by taking the offshore station (G3643) as an example. As shown in Fig. 5, the diurnal variation characteristics in the heat island intensity corresponding to the sea–land breeze day exhibited a "V"-shaped distribution. When the sea breeze started, the UHII reduced sharply, reaching its intraday minimum at ~14:00 (Beijing: GMT + 8). This was considerably lower than that of the atypical sea–land breeze day. The UHII value of the land breeze day subsequently began to increase, stabilized at 21:00 (Beijing: GMT + 8), and then continued to increase, reaching its intraday maximum at ~03:00 (Beijing: GMT + 8). This was higher than the UHII value on the atypical sea–land breeze day, but not on the typical sea–land breeze day.
and alleviate the heat island effect, whereas the land breeze could moderately increase the strength of the heat island effect. Therefore, compared with the atypical sea–land breeze day, the daily UHI variations were greater on the typical sea–land breeze day.

Both sea and land breezes had a certain effect on UHI. To further analyze the mechanism between the sea–land breezes and UHI, we combined the UHIIIs during the start and end of the sea and land breezes to obtain the correlations between the average wind speed of the overall sea and land breezes and UHIIIs in Shenzhen (Fig. 6); subsequently, both passed the confidence test with a significance level of \( \alpha = 0.05 \). The sea breeze wind speed was negatively correlated with the UHII, with a correlation coefficient of \(-0.68601\); i.e., the greater the sea breeze wind speed, the smaller the UHII, indicating that the sea breeze alleviated the heat island effect. However, land breeze wind speed and UHII were positively correlated, with the correlation coefficient of 0.81142; i.e., the greater the land breeze wind speed, the smaller the UHII, indicating that the sea breeze alleviated the heat island effect. However, land breeze wind speed and UHII were positively correlated, with the correlation coefficient of 0.81142; i.e., the greater the wind speed, the smaller the UHII, indicating that the sea breeze alleviated the heat island effect.

### DISCUSSION

Most of the currently used LCZ classification schemes employ the WUDAPT L0 method with a spatial resolution of 100 m\(^6\) or remote sensing image data (spatial resolution of 30 m–1 km), combined with building data and other GIS analysis methods\(^70,71\). For example, Chen et al.\(^70\) selected training samples based on MODIS images. They then used the random forest method to perform LCZ classification to explore the spatial distribution of thermal environments in Guangzhou and Hong Kong, two of China’s subtropical high-density cities; consequently, the two cities were found to be clearly spatially resolved. Among these methods, the WUDAPT L0 approach appears to be more suitable for performing LCZ classification over large-scale areas; however, analyzing the internal differences in small- and medium-sized cities requires higher-precision data. Based on the GIS analysis, this study used land-use and urban building data, with a spatial resolution of 10 m, to classify the LCZs. This approach resolved the low accuracy and yielded more comprehensive and accurate classification results. Additionally, this study referred to the LCZ classification scheme of Stewart & Oke\(^40\) and combined the actual situation in Shenzhen to classify the buildings more finely, which can better reflect the effect of building height and density on the strength of the heat island.

The LCZ scheme was originally designed to use the difference in air temperature to quantify the intensity of the heat island\(^9\). However, the distribution of meteorological stations is uneven, and the acquired UHII cannot cover all LCZs. The UHII value of the study area ignores the differences within the city, and it is not convenient to study the effect of LCZs on UHII. This study also calculated the air temperature results (Table 3) and found that the UHII of the building type during the daytime was higher than that of a land breeze. As the sea breeze was accompanied by damp and cold air currents, the UHI effect was greatly reduced.

#### Table 3. Summary of UHII in each LCZ in Shenzhen.

| LCZ types | Daytime (°C) | Nighttime (°C) | LCZ types | Daytime (°C) | Nighttime (°C) |
|-----------|--------------|----------------|-----------|--------------|----------------|
| LCZ1      | -0.03        | 1.31           | LCZ8      | 0.09         | 1.40           |
| LCZ2      | -0.04        | 1.33           | LCZB      | 0.11         | 1.03           |
| LCZ3      | -0.04        | 1.30           | LCZC      | 0.08         | 1.10           |
| LCZ4      | -0.01        | 1.33           | LCZD      | 0.13         | 1.06           |
| LCZ5      | 0.09         | 1.25           | LCZE      | 0.04         | 1.17           |
| LCZ6      | -0.05        | 1.32           | LCZF      | 0.12         | 0.99           |
| LCZ7      | 0.09         | 1.40           |          |              |                |
| LCZ8      | 0.09         | 0.94           |          |              |                |
| LCZ9      | -0.08        | 1.19           |          |              |                |
| LCZ10     | 0.11         | 1.07           |          |              |                |

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Fig. 6 The relationship between sea–land breeze wind speed and heat island intensity. a Land breeze, b sea breeze.
indicating that the effect of sea and land breeze on UHII was not ideal from the perspective of LST (for Shenzhen). Most previous studies have only focused on the effects of LCZs or sea–land breeze on UHIs. Furthermore, the influencing mechanism of the UHII has rarely been investigated from the comprehensive perspective of the sea–land breeze and LCZ. Therefore, Zhou et al. and Martinelli et al. discussed the impacts of different LCZ types on the surface temperature from the perspective of LCZs by simultaneously qualitatively analyzing the impacts of sea and land breezes on urban temperatures in Sendai, Japan, and Bari, Italy, respectively. However, Sendai, Bari, and Shenzhen are characterized by different climate types, and differences in the LCZ distributions within these cities. In addition, they did not quantitatively analyze the effects of sea and land breezes on the UHII. Moreover, when analyzing the influences of sea and land breezes on UHII, they focused less on the differences between these two variables under different gradients. Therefore, based on the two directions of the sea and land breezes and LCZs, this study analyzed the impacts of different LCZ types on the UHII while also determining their correlation with UHII. The average daytime and nighttime UHII values of the building LCZ types were 1.11 and 2.77 °C higher than those of the natural types, respectively. Sea breezes alleviated the UHI effect, whereas land wind moderately enhanced the UHI effect. The linear regression coefficients between the sea and land breeze wind speeds and UHII were -0.68601 and 0.81142, respectively.

To further analyze the variations in the sea and land wind speeds under different gradients and the influences of different LCZ types on the UHI strength, ArcMap 10.4 (Environmental Systems Research Institute, California, USA) was used to calculate the distances of various meteorological stations from the coastline and analyze the effects of the sea and land wind speeds and LCZ types on the UHII (UHII is obtained by air temperature) from different gradient angles (Fig. 8). Regardless of the type of LCZ at the meteorological station, the overall trends in the sea breeze wind speed and UHII values were inversely proportional, i.e., the greater the sea breeze wind speed, the smaller the UHII. Moreover, for the same LCZ type, areas farther from the coastline had lower sea breeze wind speeds and greater UHII values. For example, stations G3643, G3546, G3530, and G3634 were all LCZ4 type, and their distances to the coastline were 1.9, 2.6, 2.7, and 12.7 km, respectively. The sea breeze wind speeds were G3643 (3.55 m·s⁻¹), G3546 (3.55 m·s⁻¹), G3530 (3.55 m·s⁻¹), and G3634 (3.55 m·s⁻¹).
whereas the UHII values were $G_{3643} = -1.26 < G_{3546} = -0.08 < G_{3530} = 0.07 < G_{3634} = 0.33$. In addition, the effect of the sea breeze on the UHII for different LCZ types was investigated. For example, stations G3550 and G3501 belonged to LCZ5 and LCZD, respectively. For the influences of different LCZ types on the UHII, $UHII_{LCZ5} > UHII_{LCZD}$; however, the station results showed $UHII_{LCZ5} < UHII_{LCZD}$. This was primarily because the distance of G3550 from the coastline (9.3 km) was less than that of G3501 (11.7 km). Furthermore, $V_{LCZ5}$ was more than $V_{LCZD}$, indicating that sea breezes can alleviate the UHI effect. However, the land breeze wind speed and UHII were relatively positively correlated, i.e., the land breeze wind speed increased as the UHII increased. Moreover, for the same type of LCZ, stations farther from the coastline had lower land breeze wind speeds and showed a lower decrease in the UHII. Similarly, considering stations G3643, G3546, G3530, and G3634 as examples, the land wind speed values were as follows: $G_{3643} = 2.18 \text{ m s}^{-1} > G_{3546} = 1.37 \text{ m s}^{-1} > G_{3530} = 1.14 \text{ m s}^{-1} > G_{3634} = 0.92 \text{ m s}^{-1}$, whereas the UHII values were $G_{3643} = 2.32 > G_{3530} = 2.14 > G_{3546} = 1.88 > G_{3634} = 1.44$. The two did not show a typical positive correlation, revealing that the positive correlation between the land breeze wind speed and UHII was not strong.

The urban spatial distribution of Shenzhen differs from that of Sendai (Japan), Tianjin, and other cities in China. Its urban center is near the coastline, and the suburbs are inland. Therefore, the conclusions drawn here may differ from those of other cities. The differences in the climate types may also cause differences in the results. Thus, local conditions should be taken into consideration when performing LCZ divisions and calculating the correlations between sea and land breezes and the UHII.

This study primarily analyzed the effects of different LCZ types, typical and atypical sea–land breeze days, and different gradient sea–land wind speeds on daytime and nighttime UHII. Our results provide an important reference for urban planning and government decision-making. However, this study also has certain limitations. First, as the AST_08 data do not contain water temperature information, the potential factors that can affect the strengths of UHIs were not taken into consideration. Second, due to time constraints associated with image acquisition, the daytime and nighttime UHIs recorded in this study were not obtained for the same days. Although they were acquired under clear weather conditions within the same month, various daily conditions may have caused partial differences in the results. Finally, this study only considered the impacts of the sea and land breezes on the daytime and nighttime UHIs only in November, and seasonal differences or the UHII mechanisms were not considered. Therefore, the seasonal and regional environmental differences in the sea and land breezes and daytime and nighttime UHIs should be further explored.

**METHODS**

**Study area and data**

Shenzhen (Fig. 9), also known as “Pengcheng,” is located in southern Guangdong, China, on the eastern bank of the Pearl River Estuary, with
Daya Bay and Dapeng Bay to the east and the Pearl River Estuary and Lingding Ocean to the west. The terrain is high in the southeast and low in the northwest. Most of the area comprises low hills with gentle terraces. The region has a subtropical oceanic climate. Due to the strong influence of monsoons, the dominant wind direction is easterly-to-southeast, and southeasterly winds prevail in the summer. There are occasional monsoon lows and tropical cyclones. The northeast monsoon prevails during the remaining seasons. The weather is relatively dry, the climate is mild, and the annual average temperature is ~22.4 °C.

Data on land use, construction, administrative divisions, digital elevation models, Landsat remote sensing images, ASTER surface temperatures, and meteorological factors were used in this study (Table 4).

**LCZ classification**

An LCZ refers to a combination of similar thermal environment characteristics based on urban surface properties and morphologies. However, the LCZ classification system and its standards are not static. This study used the results of previous studies along with the urban structure and architectural characteristics of Shenzhen, to establish its LCZ classification system. Thus, an LCZ system, comprising 16 categories, was constructed, which contained 10 buildings and six natural types (Table 5). Furthermore, the study area was divided into 30 × 30 m grids using the fishing net tool in ArcGIS 10.4 (Environmental Systems Research Institute, California, USA). The building data were then mapped to the fishing net. Moreover, the building-type areas were divided according to two morphological indicators: building height and building density. The classification results were labeled under LCZ1–LCZ10. Among these, “dense” referred to a building density of >0.4, while “open” referred to a building density of <0.4. In addition, the natural type areas were divided using land-use data. The corresponding classification results were labeled as LCZA–LCZF.

**Sea and land wind speed**

A sea–land breeze is a small-to-medium-scale thermal circulation caused by the temperature difference between the sea and land. It typically overlaps with the background wind field. Along the coastline of Shenzhen, the sea–land wind direction and monsoon wind direction overlap each other, which can easily lead to errors in assessing the sea–land winds. Therefore, effectively distinguishing the sea–land winds is crucial. This study referred to the sea and land wind distinction method proposed by Wei. Thus, the wind was decomposed into a vector based on a trigonometric function, i.e., the measured wind speed at the weather station and is the wind direction.

The winds were divided into the measured, system, and local winds. Among these, the measured wind comprised hourly data recorded by various meteorological stations, system wind comprised large-scale background wind recorded daily at each station, and local wind comprised mesoscale circulation, such as sea–land and valley wind. After the vector decomposition of the measured wind values, the 24 h average values of the u component in the east–west direction and v component in the north–south direction. The corresponding formulas are as follows:

\[ u = V \cdot \sin D \]  
\[ v = V \cdot \cos D \]

where V is the measured wind speed at the weather station and D is the wind direction.

The specific formula is as follows:

\[ \vec{v}_{th} = \vec{v}_u + \vec{v}_l. \]

\[ \vec{v}_d = \frac{1}{24} \sum_{h=0}^{24} \vec{v}_{th}. \]

and

\[ \vec{v}_u = \vec{v}_{th} - \vec{v}_d. \]
where $\mathbf{V}_d^h$ is the actually measured wind vector at a given time, $h$, on day $d$, $\mathbf{V}_d^s$ is the system wind vector on day $d$, and $\mathbf{V}_d^l$ is the local wind vector at a given time, $h$, on day $d$.

Further, in this study, data of November 2019 acquired from the meteorological stations in the Futian, Bao'an, Longhua, and Nanshan districts were analyzed (except for the adjacent mountains). Based on statistics, 02:00–09:00 (Beijing: GMT + 8) was selected as the duration for land winds, while 14:00–21:00 (Beijing: GMT + 8) time was selected as the duration for sea winds; subsequently, the average wind speeds for the sea and land winds during these times were calculated.

### UHII

In addition to the LCZ theory, the definition of the heat island effect changed. When Stewart and Oke\cite{40} proposed the LCZ theory, they also redefined the intensity of the heat island effect. This study adopted the redefinition of the intensity of the heat island effect proposed by Stewart and Oke.\cite{40} The formula is as follows:

$$UHII_{LCZX} = T_{LCZX} - T_{LCZD};$$

where $UHII_{LCZX}$ represents the heat island effect intensity of LCZ$X$ and $T_{LCZX}$ and $T_{LCZD}$ are the surface temperature of the type $X$ and $D$ LCZs,

| LCZ types | Descriptions | Examples | LCZ types | Descriptions | Examples |
|-----------|--------------|----------|-----------|--------------|----------|
| LCZ1      | Compact super high-rise buildings (above 12 floors) | ![image](image1.png) | LCZA      | Dense coniferous forest and evergreen forest. | ![image](image2.png) |
| LCZ2      | Compact high-rise buildings (10-12 floors) | ![image](image3.png) | LCZB      | Sparse coniferous forest and evergreen forest. | ![image](image4.png) |
| LCZ3      | Compact middle and high-rise buildings (7-9 floors) | ![image](image5.png) | LCZC      | Open arrangement of bushes, shrubs, and short, woody trees. | ![image](image6.png) |
| LCZ4      | Compact mid-rise buildings (4-6 floors) | ![image](image7.png) | LCZD      | Grassland or herbaceous plants/crops. Few or no trees. | ![image](image8.png) |
| LCZ5      | Compact low-rise buildings (1-3 floors) | ![image](image9.png) | LCZE      | Featureless landscape of soil or sand cover. Few or no trees or plants. | ![image](image10.png) |
| LCZ6      | Open super high-rise buildings (above 12 floors) | ![image](image11.png) | LCZF      | Large, open water bodies or small bodies. | ![image](image12.png) |
| LCZ7      | Open high-rise buildings (10-12 floors) | ![image](image13.png) | LCZ8      | Open middle and high-rise buildings (7-9 floors) | ![image](image14.png) |
| LCZ9      | Open mid-rise buildings (4-6 floors) | ![image](image15.png) | LCZ10     | Open low-rise buildings (1-3 floors) | ![image](image16.png) |

Table 5. Definition and description of each LCZ type.

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respectively. In other words, the intensity of the heat island effect is the temperature difference between each LCZ and the LCZD type (low vegetation).

**DATA AVAILABILITY**

The datasets aggregated and/or analyzed during the current study are available from the corresponding author on reasonable request. Land-use dataset are available at http://data.ee.tsinghua.edu.cn:88. Building data are available at https://mapyl.esri.com/. AST_08 dataset are available at https://search.earthdata.nasa.gov/. Weather station data are available at https://opendata.sz.gov.cn/.. ASTER_GDEM data are available at http://www.gsccloud.cn/.

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**REFERENCES**

1. Mahtta, R. et al. Urban land expansion: the role of population and economic growth for 300+ cities. npj Urban Sustain. 2, 1–11 (2022).
2. Joosse, S., Hensle, L., Boonstra, W. J., Ponzelar, C. & Olsson, J. Fishing in the city for urban gradient in Worcester, Massachusetts using in-situ Thermochrons and Landsat-8 Thermal Infrared Sensor (TIRS) data. Geosci. Remote Sens. 57, 845–864 (2020).
3. Elmes, A. et al. Mapping spatiotemporal variability of the heat island across an urban gradient in Worcester, Massachusetts using in-situ Thermochrons and Landsat-8 Thermal Infrared Sensor (TIRS) data. Geosci. Remote Sens. 57, 845–864 (2020).

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54. Oliveira, A., Lopes, A. & Niza, S. Local climate zones in five southern European cities: An improved GIS-based classification method based on Copernicus data. Urban Clim. 33, 100631 (2020).
55. Yang, J. et al. Investigating the diversity of land surface temperature characteristics in different scale cities based on local climate zones. Urban Clim. 34, 100700 (2020).
56. Zhao, C. Linking the local climate zones and land surface temperature to investigate the surface urban heat island, a case study of San Antonio, Texas, US. ISPRS Ann. Photogramm. Remote Sens. Spatial Inform. Sci. 3, 277–283 (2018).
57. Zhao, C. Linking the local climate zones and land surface temperature to investigate the surface urban heat island in Texas. Gisci. Remote Sens. 57, 1083–1101 (2020).
58. He, B., Wang, J., Liu, H. & Ulpiani, G. Localized synergies between heat waves and urban heat islands: Implications on human thermal comfort and urban heat management. Environ. Res. 193, 110584 (2021).
59. Lu, X., Yang, J., Sun, W. & He, B. Suitability of human settlements in mountainous areas from the perspective of ventilation: a case study of the main urban area of Chongqing. J. Clean. Prod. 310, 127467 (2021).
60. Ren, C. et al. Investigating the urban heat and cool island effects during extreme heat events in high-density cities: A case study of Hong Kong from 2000 to 2018. Int. J. Climatol. 41, 6736–6756 (2021).
61. Xie, P., Yang, J., Sun, W., Xiao, X. & Cecilia Xia. J. Urban scale ventilation analysis based on neighborhood normalized current model. Sustain. Cities Soc. 80, 103746 (2022).
62. He, B., Ding, L. & Prasad, D. Outdoor thermal environment of an open space under sea breeze: A mobile experience in a coastal city of Sydney, Australia. Urban Clim. 31, 100567 (2020).
63. Park, M. & Chae, J. Features of sea–land-breeze circulation over the Seoul Metropolitan Area. Geosci. Lett. 5, 1–12 (2018).
64. Wang, Y. et al. Impact of land surface heterogeneity on urban heat island circulation and sea-land breeze circulation in Hong Kong. J. Geophys. Res. Atmos. 8, 4332–4352 (2017).
65. Zhou, Y. et al. Sea breeze cooling capacity and its influencing factors in a coastal city. Building Environ. 166, 106408 (2019).
66. Ramamurthy, P. & Sangobanwo, M. Inter-annual variability in urban heat island intensity over 10 major cities in the United States. Sustain. Cities Soc. 26, 65–75 (2016).
67. Wang, Q., Zhang, C., Ren, C., Hang, J. & Li, Y. Urban heat island circulations over the Beijing-Tianjin region under calm and fair conditions. Build. Environ. 180, 107063 (2020).
68. Shen, L., Sun, J. & Yuan, R. Idealized large-eddy simulation study of interaction between urban heat island and sea breeze circulations. Atmos. Res. 214, 338–347 (2018).
69. Dian, C., Pongrácz, R., Dezső, Z. & Bartholy, J. Annual and monthly analysis of surface urban heat island intensity with respect to the local climate zones in Budapest. Urban Clim. 31, 100573 (2020).
70. Chen, X., Xu, Y., Yang, J., Wu, Z. & Zhu, H. Remote sensing of urban thermal environments within local climate zones: a case study of two high-density subtropical Chinese cities. Urban Clim. 31, 100568 (2020).
71. Yang, J. et al. Understanding land surface temperature impact factors based on local climate zones. Sustain. Cities Soc. 69, 102818 (2021).
72. Mughal, M. O., Li, X. & Norford, L. K. Urban heat island mitigation in Singapore: evaluation using WRF/multilayer urban canopy model and local climate zones. Urban Clim. 34, 100714 (2020).
73. Skarbit, N., Stewart, I. D., Unger, J. & Gál, T. Employing an urban meteorological network to monitor air temperature conditions in the ‘local climate zones’ of Szeged, Hungary. Int. J. Climatol. 37, 580–596 (2017).
74. Zhang, Y., Zhang, J., Zhang, X., Zhou, D. & Gu, Z. Analyzing the characteristics of UHI (Urban Heat Island) in summer daytime based on observations on 50 sites in 11 LCZ (Local Climate Zone) Types in Xi’an, China. Sustainability 13, 83 (2021).
75. Zhou, X. et al. Evaluation of urban heat islands using local climate zones and the influence of sea-land breeze. Sustain. Cities Soc. 55, 102060 (2020).
76. Martellini, A., Kolokotsa, D. & Fiorito, F. Urban heat island in Mediterranean coastal. cities: the case of Bari (Italy). Climate 8, 79 (2020).
77. Wei C. Analysis on the characteristics of sea and land breeze climate in coastal areas of Jiangsu coastal areas. (Nanjing University of Information Technology, 2012).
78. Gong, P. et al. Stable classification with limited sample: transferring a 30-m resolution sample set collected in 2015 to mapping 10-m resolution global land cover in 2017. Sci. Bull. 64, 370–373 (2019).

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AUTHOR CONTRIBUTIONS
J.Y. contributed to all aspects of this work; J.X. wrote the main manuscript text, Y.Z., X., and J.C.X. conducted the experiment and analyzed the data.

COMPETING INTERESTS
The authors declare no competing interests

ADDITIONAL INFORMATION
Correspondence and requests for materials should be addressed to Jun Yang or Yuqing Zhang.

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