How does 2D and 3D of urban morphology affect the seasonal land surface temperature in Island City? A block-scale perspective

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ABSTRACT

The global climate warming caused by urbanization has significantly affected the urban environment. Whilst land surface temperature (LST) is an important factor reflecting urban temperature, previous research on LST mostly focused on two-dimensional (2D) factors and rarely mentioned about the role of three-dimensional (3D) factors, particularly the LST variation characteristics of island cities. Therefore, this study examined the seasonal variation characteristics of urban LST by analyzing the impact of 2D and 3D urban morphology factors of different urban block types on LST in Xiamen Island. The main results are as follows. First, compact low layer (CL), a block type with a higher density of low-rise buildings, has a higher LST in any season. Under the same block density (BD), the higher the block average height (BH), the lower the LST. Second, among the 2D urban morphology factors, normalized difference vegetation index (NDVI) was the main factor for cities to reduce urban LST, especially in summer, while normalized difference built-up index (NDBI) was the opposite. Different from land cities, we found a positive correlation between modified normalized difference water body index (MNDWI) and LST in autumn and winter. Third, in the 3D urban morphology factors, sky view factor (SVF) was significantly positively correlated with LST, while building fluctuation (BF) was negatively correlated. The higher the SVF, the worse the radiation shielding effect between buildings. On the contrary, the higher the BF, the higher the building undulation, and the better the building radiation shielding. These findings should provide some quantitative insights for the future construction and planning of island cities, which can be used to improve the thermal environment of island cities and support the sustainable development of cities.

1. Introduction

With the progress of urbanization, population is gradually moving to cities. According to the World Cities Report 2022, the world's urbanization rate has reached 56% in 2021, and it is expected to exceed 68% in 2050 (United-Nations-Human-Settlements-Programme, 2022). Cities have become the main places for humans to live and work, and the proportion of the population in urban area will continue to grow even larger (Xu et al., 2020). To meet the production and living needs of urban residents, urban expansion has inevitably occurred, which has changed the pattern and morphology of the city (Wei and Ye, 2014; Zhou et al., 2022; Zhu et al., 2019). However, huge change in urban pattern has also brought many environmental problems to the city, including global warming (Wang et al., 2022a, Yuan et al., 2022), air

pollution (Zhu et al., 2021; Zhu et al., 2019), biodiversity declines (Ruas et al., 2022; Wang et al., 2022b) and other global issues. Especially, global warming endangers the balance of the natural ecosystem (Schirpke and Ebner, 2022; Zhang et al., 2022a), causes natural disasters (Bouchard et al., 2022) and threats to the survival and health of humans (Xing et al., 2022), which seriously threatened the survival of human beings (Liu et al., 2022).

Land surface temperature (LST) is crucial in urban climatology, which is an important indicator to reflect the change of urban global warming (Pandey et al., 2022; Zhou et al., 2021). Through LST monitoring, we can understand the urban climate change (Nguyen et al., 2022), urban heat island effect (Hidalgo-García and Arco-Díaz, 2022), etc. To understand the impact of urbanization on urban LST, experts and scholars have conducted a comprehensive discussion. Researchers have

studied the correlation between the spatio-temporal change characteristics of urban land use/land cover and urban LST (Kumar et al., 2022; Yeneneh et al., 2022), and then investigated the impact mechanism of urban landscape pattern index and urban LST (Bekele et al., 2022; Xiang et al., 2022). From the findings of previous studies, it can be seen that the characteristics of urban land use structure have a significant impact on urban LST. Nevertheless, at present, most of these studies focus on the impact of two-dimensional (2D) urban morphology on LST. Comprehensive investigations have found that the three-dimensional (3D) urban morphology also has a significant impact on LST (Hu et al., 2020; Li and Hu, 2022; Zhang et al., 2022b). These studies analyzed the change characteristics of urban LST from the 3D indicators of urban building density, floor area ratio, sky view factor (Miao et al., 2020) and other indicators, which also confirmed that urban 3D urban morphology has a greater impact on urban LST (Azmi et al., 2021; Chen et al., 2020). The previous works on LST in 2D and 3D urban morphology have provided important references for rational urban planning to cope with the impact of urban climate change. The characteristics of urban morphology are relatively diverse. Although the addition of 3D urban morphological features has greatly improved the integrity of urban morphological features, studies on the 3D differences within the block were limited (Lei et al., 2022). Therefore, this study attempts to increase the urban building height fluctuation, which had been proven as a crucial indicator on urban LST (Li et al., 2021). It will complement and improve the variation characteristics of the 3D urban morphology, so as to better interpret the urban morphological characteristics.

The existing research on the relationship between urban morphological characteristics and LST mainly focuses on land cities, while research on island cities is relatively rare. However, the urbanization processes of land cities and island cities are quite different from each other (Pan et al., 2022). Therefore, exploring the impact of urban morphological characteristics of island cities on LST can provide a reference for island cities on how to reduce disaster risk and adapt to climate change (Rahayu et al., 2018). To further explore the impact of urban 2D and 3D morphological characteristics on LST, we selected island cities as study area to fill the gap of the research object type. Different from the construction and development of land cities, island cities have obvious geographical boundaries due to their geographical characteristics (Farhan and Lim, 2011). Therefore, it is difficult for island cities to radiate outward to develop urban construction like land cities. In addition, the cost of reclamation and its impact on ecology render such kind of urban expansion model unfeasible. The construction and development of island cities are mainly carried out on the island, or linked to the development of land cities (Nae-WenKuo and Pei-HunChen, 2009; Tzanopoulos and Vogiatzakis, 2011). Due to the feature of island cities, the urban morphology of island cities is different from that of land cities (Liu et al., 2021). To some extent, the urbanization process of the island city form can be understood as the result of the interaction between urban development and natural geographical environment (Pan et al., 2022). Moreover, compared to inland cities, more attention should be paid to the marine environment and urban form for the planning and management of the island cities in addition to the change in LULC closely related to the urbanization process (Zhang et al., 2022c). Selecting island cities as research objects can more clearly reflect the impact of urbanization on LST than land cities.

Xiamen Island, an island city with great economic development in China, is a special economic zone of China with a high level of urbanization (Fang et al., 2020), which provides sufficient and rich data sources of urban morphological characteristics for this study. By studying the influence of Xiamen Island's 2D and 3D urban morphological characteristics on LST, we can comprehensively interpret the relationship between different urban morphological characteristics of island cities and LST. Therefore, this study aims to (1) explore the characteristics of LST changes in island cities in different seasons; (2) examine whether the relationship between different urban block types (UBT) and LST is different in different seasons; (3) explore the

correlation between 2D and 3D urban morphological characteristics of different urban block types and LST in different seasons; (4) discuss the contribution value of 2D and 3D urban morphological factors to LST in different seasons on the block scale. The study outcome is expected to provide important reference data to support the planning, construction and development of other island cities to reduce the negative impact of global warming.

2. Materials and methods

2.1. Study area

Xiamen (24° 23 'N- 24° 54′N, 117° 53 'E- 118° 26′E) is located along the southeast coast of China (Fig. 1). It has a subtropical marine monsoon climate, with an average annual rainfall of about 1200 mm. It is one of the first reform and opening-up special economic zones in China (Zhu et al., 2022). It is a civilized city, a national cultural and ecological protection zone, a national health city, and a national ecological garden city. The city is dominated by coastal plains, platforms and hills. The main urban area of Xiamen is located in Xiamen Island, with an area of 158 km^2 and a population of 1.2807 million. In 2021, Xiamen's GDP reached 703.389 billion Chinese yuan, with an urbanization rate of 89.41%. It can be seen that Xiamen has a relatively high level of urbanization and belongs to the first-tier developed city, especially Xiamen Island. However, with the concentration of population and the expansion and construction of Xiamen Island (Li et al., 2011), the environmental carrying capacity of Xiamen Island has also been challenged, leading to a series of environmental problems, such as air pollution (Fu et al., 2018), noise pollution and urban heat island effect (Liu et al., 2021), which seriously affect the normal production and life of urban residents (Zhu et al., 2020). Therefore, this study selected Xiamen Island as a typical sample to explore how urban morphological characteristics affect LST in island cities.

2.2. Datasets

2.2.1. LST and surface biophysical parameters datasets

The remotely sensed dataset used in this study was collected from the Geospatial Data Cloud (https://www.gscloud.cn/) Landsat8 OLI/TRIS (Operational Land Imager, OLI; Thermal Infrared Sensor, TRIS) images with an accuracy of 30 m. The data selection criteria are: (1) pick the remote sensing images with cloud cover<10% as the research data to ensure that the collected LST data will not be interfered by clouds; (2) sunny day is preferred to reduce the problem of inaccurate LST caused by weather; (3) the selected data time points are the same to reduce the temperature difference caused by different times (Yao et al., 2022a). According to the climate characteristics of China and the division of seasons in "Xiamen Climate Annual Report", this study defines March to May, June to August, September to November and December to February as spring, summer, autumn and winter respectively. A total of 4 remote sensing maps (2020.03, 2021.07, 2020.09, 2021.02) were collected as data sources for studying the spatial distribution of LST in spring, summer, autumn and winter respectively in Xiamen Island. All selected periods of remote sensing maps are sunny, without rainstorm, hail, typhoon, meteorological drought and pollution, which can better represent the local climate conditions. To analyze the impact of Xiamen Island's surface biological parameters on LST, we used the remote sensing map in summer as the data source of Normalized difference vegetation index (NDVI), Normalized difference built-up index (NDBI) and modified normalized difference water body index (MNDWI) to obtain relevant data.

2.2.2. The data source of urban morphological characteristics

The data of urban morphological characteristics were divided into street boundary and building contour data, which were sourced from the Urban blocks in 63 Chinese cities 2020 data of Beijing Urban Laboratory
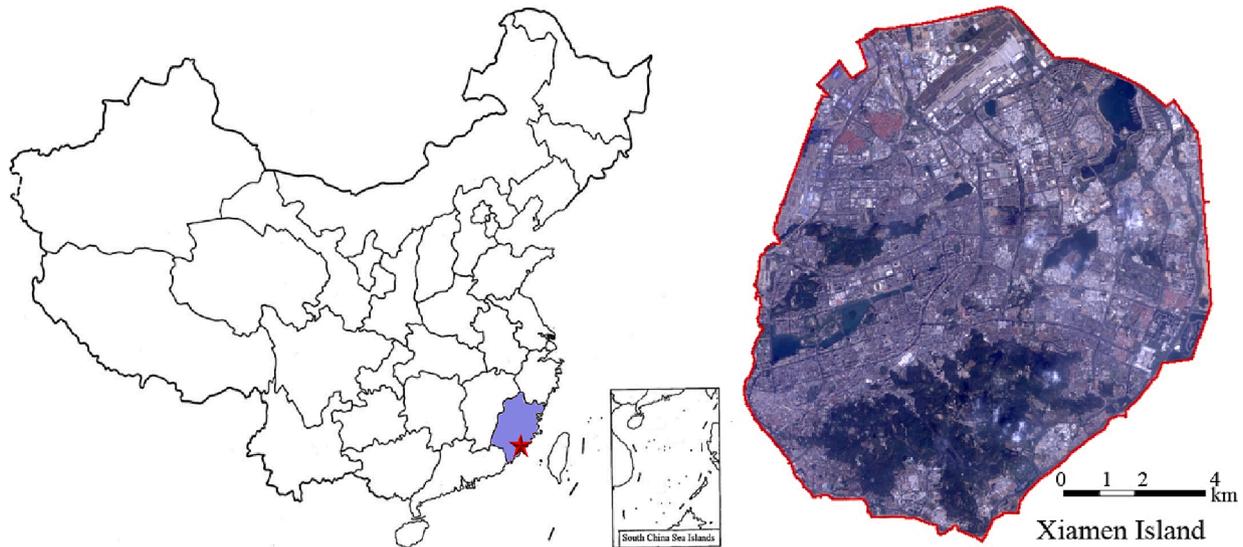
Fig. 1. The location of study area.

(https://www.beijingcitylab.com/). To ensure the quality of data, we formulated these data processing conditions: (1) the block area is not<1 ha; (2) the block is located in the main urban area of the city (Yao et al., 2022a). Based on these two screening conditions, we determined 1215 blocks and 45,755 building outlines in Xiamen Island. Based on these datasets, we analyzed the 2D and 3D urban morphology factors of Xiamen Island.

2.3. Methods

2.3.1. LST retrieval

The LST retrieval used in this study is similar to the radiative transfer equation method used in Wang, and Zhen (Li and Hu, 2022; Weng et al., 2004). Previous studies have reported that compared to other algorithms, the LST calculated using the radiative transfer equation algorithm is the most highly accurate (Yu et al., 2014; Yu et al., 2017). The LST retrieval contains three main steps. First, a radiometric rescaling factor is used to convert the digital (DN) of the thermal infrared band into radiation. Second, NDVI, vegetation fraction (Fv) and surface emissivity (ε) are calculated. Finally, the LST is calculated according to the brightness and temperature ε. Using Landsat-8 TIRS to measure the temperature change of the scene by TIRS band 10, the thermal infrared channel radiation Bi (Ti) measured at the top of the atmosphere can be calculated as:

$$L_\lambda = [\varepsilon B(T_S) + (1-\varepsilon)L\downarrow]\tau + L\uparrow \tag{1}$$

where $L\lambda$ represents the surface thermal radiation intensity received by TIRS; ε represents the surface emissivity, which can be calculated according to the NDVI value (Zhang et al., 2019); $L\downarrow$, $L\uparrow$ and τ are the atmospheric emissivity of downflow, the atmospheric emissivity of upflow and the atmospheric transmittance, respectively, which can be obtained from the NASA (National Aeronautics and Space Administration) atmospheric correction calculator (https://atmcorr.gsfc.nasa.gov/) (Yao et al., 2022b). T_s represents the surface temperature in Kelvin, and $B(T_s)$ represents the thermal radiation of black body, which can be determined according to Planck's law:

$$B(T_S) = \frac{L_\lambda - L\uparrow - \tau(1-\varepsilon) \times L\downarrow}{\tau\varepsilon} \tag{2}$$

Finally, we get the T_S calculation as follows:

$$T_S = \frac{K_2}{\ln\left(\frac{K_1}{B(T_S)} + 1\right)} \tag{3}$$

where K1 and K2 are 774.89 (Wm-2sr-1 μm-1) and 1321.08 K for Landsat-8 TIRS band 10, respectively.

2.3.2. 2D and 3D urban morphology factors

In the selection of influencing factors of 2D and 3D urban morphological characteristics, we referred to the research of Yao, Liang and Yunfeng (Hu, Dai and Guldmann, 2020; Yao et al., 2022a; Zhou et al., 2022), which all pointed out that the indicators of surface biophysical parameters have a relatively significant impact on LST. The adopted these screening criteria: (1) it has been recognized and applied by a large number of researchers; (2) it has been proved to be effective theoretically and practically; (3) redundancy influencing factors are not filtered repeatedly. According to the above criteria, we screened four 2D urban morphology factors, namely building area (BA), NDVI, NDBI, MNDWI. There are five 3D urban morphology factors, namely, block average height (BH), building fluctuation (BF), floor area ratio (FAR), block density (BD), and sky view factor (SVF) (Table 1).

2.3.3. Classification of urban block types

To better understand the impact of 2D and 3D urban morphology factors on urban LST, different urban block types (UBTs) were subdivided into six types. The subdivision conditions are: (1) each type can reflect the characteristics of different block types; (2) there are great number of all UBTs in the study area; (3) the selected blocks will not be completely independent of others. Following Yao, Li and Hu (Chen, Han and De Vries, 2020; Hu, Dai and Guldmann, 2020; Li and Hu, 2022), we classified BD < 0.35 and BD ≥ 0.35 as open block and compact block,

Table 1
The Explanation of 2D and3D urban morphology factors.

	Urban morphology factors	Explanation
2D	Building area (BA)	The building area in the block
	NDVI	Normalized difference vegetation index
	NDBI	Normalized difference built-up index
	MNDWI	Modified normalized difference water body index
3D	Block average height (BH)	The average height of building with the block.
	Building fluctuation (BF)	The fluctuation height of building with the block.
	Floor area ratio (FAR)	The ratio of the total floor area to the total block area.
	Block density (BD)	The ratio between the building coverage area and the total block area.
	Sky view factor (SVF)	The mean value of SVF in a block.

respectively. we divided BH into three levels, i.e., BH < 9 m, 9 m ≤ NF < 21 m and NF ≥ 21 m, which represent low, middle and high block forms, respectively. Finally, we divided the UBT into open low layer (OL), open middle layer (OM), open high layer (OH), compact low layer (CL), compact middle layer (CM) and compact high layer (CH).

2.3.4. The distribution index of different urban block on LST

To explore the influence characteristics of different types of residential areas on LST in different seasons, we introduced the distribution index model (DI) (Yao et al., 2022a), graded LST, and took the highest temperature level (HTL) to analyze its dominance in different UBT to determine which type of block is dominated by HTL. The calculation formula is as follows:

$$DI = \frac{R_{hi}/R_i}{R_h/R} \tag{4}$$

where R_{hi} and R_h are the total HTL regions in the i_{th} UBT and the whole study area, respectively. S_i and S represent the total area of the i_{th} UBT and the study area, respectively. If DI value is greater than 1, HTL area is
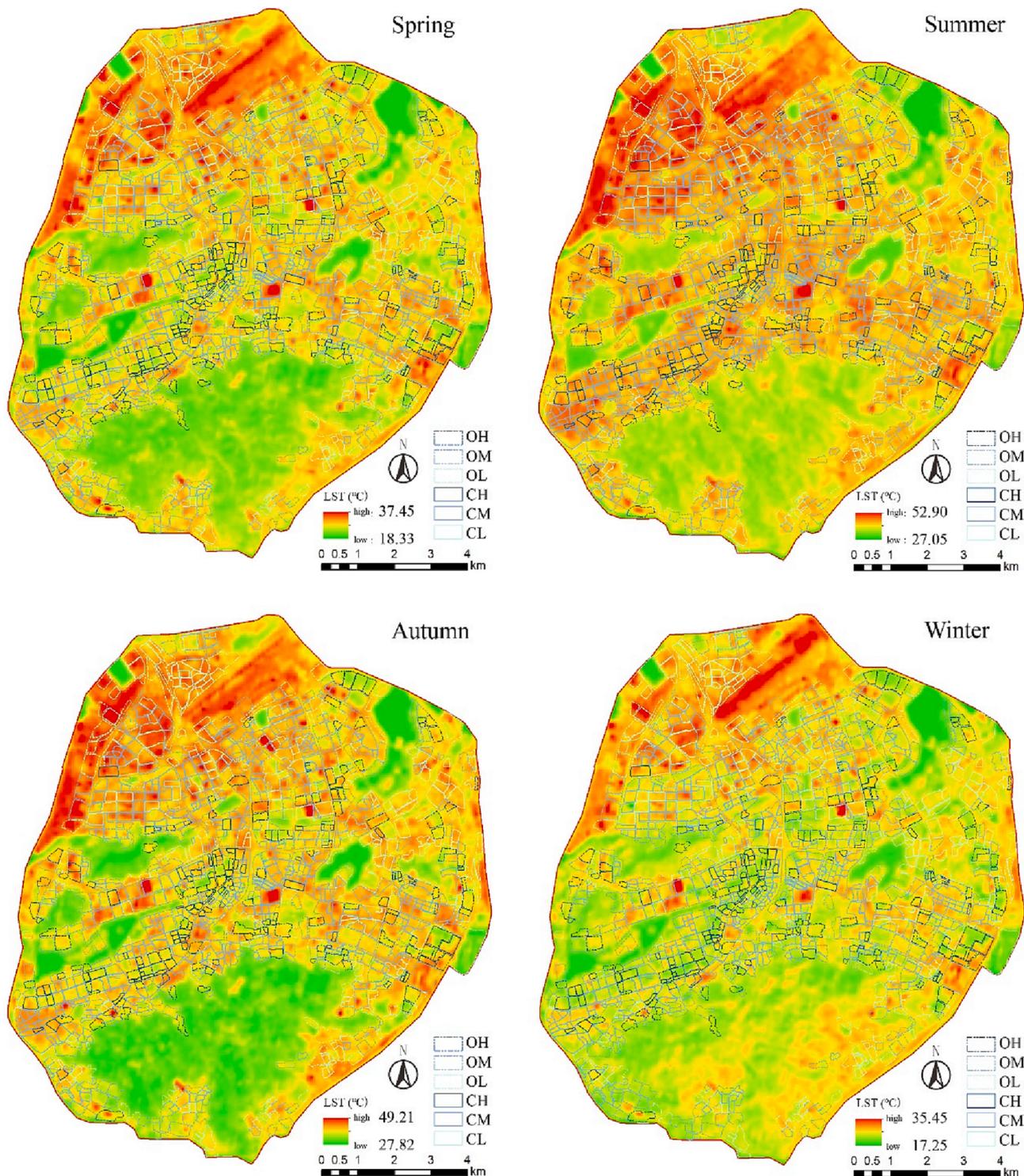

Fig. 2. Spatial distribution of LST during different seasons in Xiamen island.

the dominant distribution in the i_{th} UBT, which means that this type of UBT has an impact on the urban thermal environment.

2.3.5. Random forest regression model

The random forest model was proposed by Breiman (2001) (Breiman, 2001), which is a nonlinear and nonparametric integration algorithm based on regression tree. Given its high accuracy relative to other traditional regression models, it can be used to quantify the influence and relative contribution of independent variables. It is widely recognized and promoted by various research fields (Ferrer Palomino et al., 2022; Wang et al., 2022c). In this study, LST was taken as the dependent variable, and nine 2D and 3D urban morphology factors were selected as independent variables to conduct research using random forestry regression model. The impact of each independent variable on LST was analyzed.

3. Results

3.1. Spatial distribution characteristics of seasonal LSTs

By analyzing the LST of Xiamen Island in four seasons, the results show that the LST of Xiamen Island is 18.33–37.45℃ in spring, 27.05–52.09℃ in summer, 27.82–49.21℃ in autumn and 17.25–35.45℃ in winter. Fig. 2 clearly shows that the higher LST mainly occurred in the northwest and some central areas of Xiamen Island in four seasons (where the urban density was relatively high), but less adjacent to green spaces and water bodies. The LST in the south was

lower than others, mainly because it was adjacent to large areas of forest land and low-density urban buildings.

3.2. Seasonal impact of UBT on LST

To further explore the relationship between urban morphological characteristics and LST, we analyzed the impact of UBT on LST (Fig. 3). On the whole, the three urban morphology types with higher BD (CL, CM, CH) have higher LST than those with lower BD (OL, OM, OH). From the perspective of each urban morphology type, the LST of CL region was significantly higher than those of other urban morphology types in four seasons (P < 0.05), while OH was the opposite. The LST of UTB in descending order followed CL > OL > CM > OM > CH > OH. These results reflect a positive correlation between LST and BD; and a negative correlation between LST and BH.

Based on the distribution index model (DI), we verified the distribution of the highest temperature in UBTs. The results show (Table 2) that except in summer, the distribution dominance of the HTL in CL was higher, and CM was slightly higher than CL in summer. The highest DI appeared in CM in summer, up to 3.03, followed by CL of 2.94. Regardless of the season, the distribution of the highest temperature in OH was the least, especially in winter, with a dominance of only 0.16. Overall, the DI distribution index confirms the significant impact of BD on LST. Given the higher LST of blocks at higher BD, the block of compact block is also higher than the LST under the same BH condition.

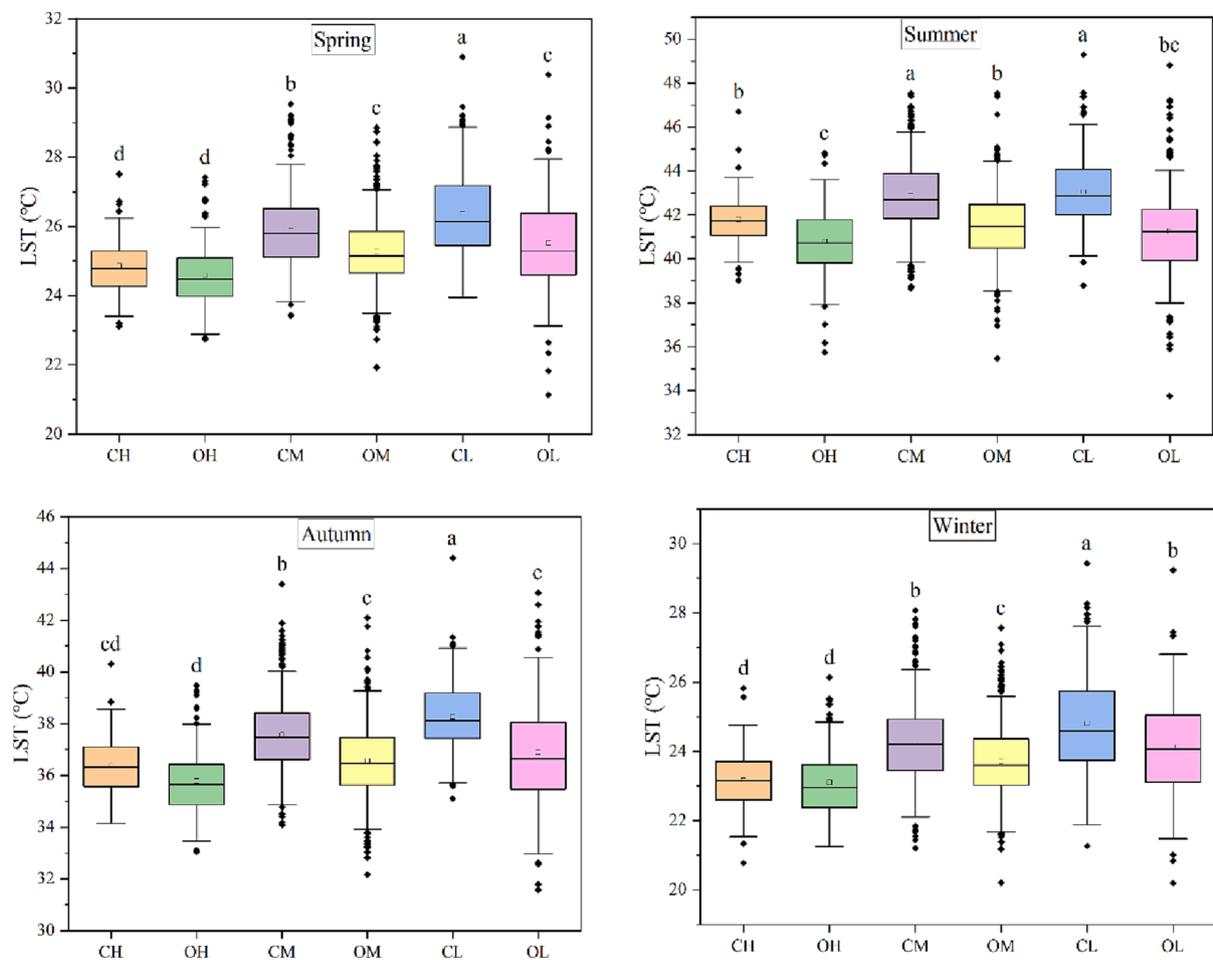**Fig. 3.** Effect of UBTs on LST across seasons. Notes: (The black line and hollow square represent the median and mean of LST in different UBTs, respectively. For each season, different letters (a–e) indicate significant differences in LST among different UBTs at P < 0.05. In different UBTs, the expression of the same letter means not significant, while the expression of different letters is significant.).

Table 2
Seasonal value of DI in different UBT.

Seasonals				
Block types	Spring	Summer	Autumn	Winter
CH	0.23	1.12	0.53	0.20
OH	0.37	0.52	0.38	0.16
CM	1.15	3.03	1.79	0.83
OM	0.70	1.24	0.90	0.48
CL	2.02	2.94	2.70	1.70
OL	1.16	1.33	1.43	0.87
	Low			High

3.3. Correlation between 2D and3D urban morphology factors and LST in different seasons

The correlation between different urban morphology factors and LST showed distinct differences in the four seasons of Xiamen Island. Whether 2D or 3D urban morphology factors have a strong correlation with the LST of Xiamen Island in four seasons (Table 3). The comparison of correlation strength suggests that SVF in 3D indicators had the highest significant positive correlation effect on LST, and the correlation value was the largest in spring and winter, showing 0.470 (P < 0.01). Secondly, NDVI in 2D urban indicators had a strong positive correlation effect on LST, which was the most obvious in summer and autumn, reaching −0.375 and −0.391, respectively. NDBI and BD also showed a strong positive correlation with the LST. These two indicators jointly confirm that the LST increased with the increase of BD and building index. BH and BF showed a negative correlation with the LST of the four seasons, indicating that the LST decreased with the increase of the BH and BF. The shadow and air duct generated by the change in building height and building deformation can effectively reduce LST. FAR was negatively correlated with LST except in summer. The impact of MNDWI on LST in four seasons varied from that in other cities, showing a positive correlation with LST in autumn and winter, which could be related to the characteristics of island cities.

3.4. Seasonal influence of 2D and 3D urban morphology factors on LSTs

To rigorously examine the role of 2D and 3D urban morphology factors in different UBTs on LST, we draw the following results through RF analysis (Fig. 4). In spring, NDBI (18.43%) was the largest urban morphology factor contributing to the LST of Xiamen Island, followed by NDVI (18.13%). FAR (31.51%) had the largest LST contribution to CH, followed by SVF (19.31%). The largest LST contribution to CM was NDVI (24.17%), followed by NDBI (19.73%). The largest LST contribution to CL was MNDWI (24.38%), followed by NDVI (16.67%). The largest LST contribution value of urban morphology factors in OH, OM and OL were SVF, showing 28.03%, 19.25% and 20.01%, respectively. The second LST contribution value to OH, OM and OL were FAR (20.27%), BA (14.53%) and NDVI (16.16%), respectively.

Table 3
Results of correlation between urban morphology factors and seasonal LST.

Seasonals Urban factors		Spring	Summer	Autumn	Winter
2D	BA	0.098**	0.024	0.082**	0.095**
	NDVI	−0.313**	−0.375**	−0.391**	−0.272**
	NDBI	0.304**	0.388**	0.381**	0.240**
	MNDWI	0.047	0.043	0.061*	0.085**
3D	BH	−0.290**	−0.176**	−0.261**	−0.282**
	BF	−0.247**	−0.103**	−0.220**	−0.277**
	FAR	−0.187**	0.013	−0.136**	−0.222**
	BD	0.286**	0.384**	0.319**	0.222**
	SVF	0.470**	0.274**	0.442**	0.470**
	Low				High

* and ** represent *P* < 0.05 and *P* < 0.01 in the significance test, respectively.

Different from spring, the urban morphology factor with the largest LST contribution to Xiamen Island in summer was NDVI (20.39%), followed by NDBI (17.34%). UBTs with similar LST contribution values to Xiamen Island also include OH, CM and OL. The largest LST contribution to CH is NDBI (25.26%), followed by BH (24.22%). OM had the largest contribution value of BA (20.56%) to its LST, followed by NDVI (17.85%). The CL contribution in summer was similar to that in spring.

In autumn, the urban morphology factors with the largest LST contribution to Xiamen Island were consistent with those in summer, the NDVI and NDBI showed great impact on LST. UBTs with similar contribution values to Xiamen Island also include OH, CM, CL and OL, which were similar to those in summer. The changes in CH and OM were quite different from those in spring and summer. The largest contribution to LST was FAR (27.14%), followed by NDBI (17.34%). The largest LST contribution to OM was NDVI (24.28%), followed by SVF (17.90%).

In winter, the urban morphology factors with the largest contribution value to LST of Xiamen Island were consistent with those in spring, namely NDBI (21.22%) and NDVI (17.10%). The largest LST contribution to CH was FAR (32.22%), followed by SVF (19.01%). The largest LST contribution to CM was NDBI (21.24%), followed by NDVI (19.91%). The largest LST contribution to CL was MNDWI (29.23%), followed by NDVI (18.32%). The largest LST contribution to OL was FAR (22.18%), followed by SVF (15.82%). The LST with the largest contribution value to OH and OM was SVF, namely 30.42%, and 21.48% respectively. While the LST with the second contribution values were FAR (18.72%), and BF (17.92%).

4. Discussion

4.1. Seasonal impact of different UBTs on LST in island city

We found that UBT with higher BD has higher LST than UBT with lower BD in any seasons. This indicates increasing urban construction in the process of urbanization, which has affected the LST of the city and ultimately led to a more significant high LST (Adulkongkaew et al., 2020; Ghosh et al., 2022). The study also found that with the increase of building height, the LST of compact or open urban blocks decreased. The results of the distribution index also confirmed this situation. HTL was more likely to appear in dense low-rise and middle-rise buildings. This result is also consistent with Yao et al. (2022a), which demonstrated that the LST of the block type with the higher building was lower than that of the block type with lower building height, which might be affected by the function of building shadows provided by high-rise buildings to absorb solar radiation (Taripanah and Ranjbar, 2021). As required by the fire protection conditions of high-rise buildings, the open space and building spacing specified in the design can provide more convenience for air circulation. Also, the open space will provide more space for greening, which leads to lower LST and UHI intensity in the high-rise space type than that in the low-rise space type (Yao et al., 2022b). On the contrary, compact low-rise buildings, due to their narrow street space and high density of building space, not only lead to heat dissipation but also limited space for greening and less green area (Xiang et al., 2022).

4.2. Seasonal impact of 2D and3D urban morphology factors on LST in different UBTs

Urbanization has greatly changed the urban morphological characteristics. Therefore, this study evaluated the impact of urban morphological characteristics on the LST of UBTs from the perspective of 2D and 3D urban morphological factors. Among the 2D factors, we confirmed that NDVI has a significant cold island effect on urban LST (Kumar, Babu, Anusha and Rajasekhar, 2022). NDVI has significant cooling benefits at all UBTs in four seasons. The RF calculation results showed that its cooling benefits were particularly significant in summer and autumn. This is consistent with the research of most experts and scholars
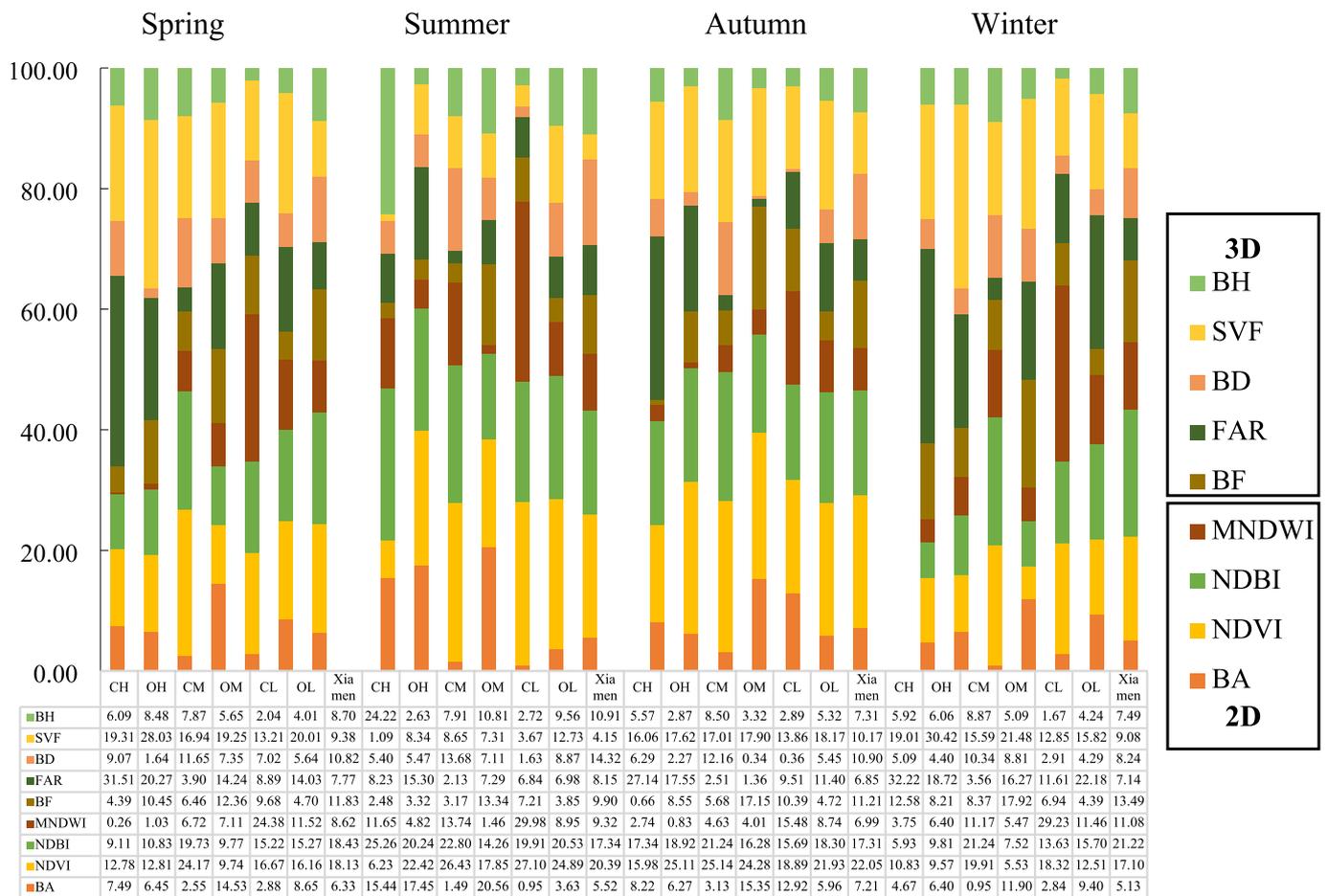
	Spring							Summer							Autumn							Winter						
	CH	OH	CM	OM	CL	OL	Xiamen	CH	OH	CM	OM	CL	OL	Xiamen	CH	OH	CM	OM	CL	OL	Xiamen	CH	OH	CM	OM	CL	OL	Xiamen
BH	6.09	8.48	7.87	5.65	2.04	4.01	8.70	24.22	2.63	7.91	10.81	2.72	9.56	10.91	5.57	2.87	8.50	3.32	2.89	5.32	7.31	5.92	6.06	8.87	5.09	1.67	4.24	7.49
SVF	19.31	28.03	16.94	19.25	13.21	20.01	9.38	1.09	8.34	8.65	7.31	3.67	12.73	4.15	16.06	17.62	17.01	17.90	13.86	18.17	10.17	19.01	30.42	15.59	21.48	12.85	15.82	9.08
BD	9.07	1.64	11.65	7.35	7.02	5.64	10.82	5.40	5.47	13.68	7.11	1.63	8.87	14.32	6.29	2.27	12.16	0.34	0.36	5.45	10.90	5.09	4.40	10.34	8.81	2.91	4.29	8.24
FAR	31.51	20.27	3.90	14.24	8.89	14.03	7.77	8.23	15.30	2.13	7.29	6.84	6.98	8.15	27.14	17.55	2.51	1.36	9.51	11.40	6.85	32.22	18.72	3.56	16.27	11.61	22.18	7.14
BF	4.39	10.45	6.46	12.36	9.68	4.70	11.83	2.48	3.32	3.17	13.34	7.21	3.85	9.90	0.66	8.55	5.68	17.15	10.39	4.72	11.21	12.58	8.21	8.37	17.92	6.94	4.39	13.49
MNDWI	0.26	1.03	6.72	7.11	24.38	11.52	8.62	11.65	4.82	13.74	1.46	29.98	8.95	9.32	2.74	0.83	4.63	4.01	15.48	8.74	6.99	3.75	6.40	11.17	5.47	29.23	11.46	11.08
NDBI	9.11	10.83	19.73	9.77	15.22	15.27	18.43	25.26	20.24	22.80	14.26	19.91	20.53	17.34	17.34	18.92	21.24	16.28	15.69	18.30	17.31	5.93	9.81	21.24	7.52	13.63	15.70	21.22
NDVI	12.78	12.81	24.17	9.74	16.67	16.16	18.13	6.23	22.42	26.43	17.85	27.10	24.89	20.39	15.98	25.11	25.14	24.28	18.89	21.93	22.05	10.83	9.57	19.91	5.53	18.32	12.51	17.10
BA	7.49	6.45	2.55	14.53	2.88	8.65	6.33	15.44	17.45	1.49	20.56	0.95	3.63	5.52	8.22	6.27	3.13	15.35	12.92	5.96	7.21	4.67	6.40	0.95	11.90	2.84	9.40	5.13

Fig. 4. Contribution rate of 2D and 3D urban morphology factors to seasonal LST in different UBTs.

(Mathew et al., 2022; Yang et al., 2016), which reported the importance of vegetation to mitigate urban heat island effect, regardless of in islands or in mainland cities (Julien and Sobrino, 2009). In contrast to NDVI, NDBI showed a significant positive correlation with LST in four seasons, and the contribution value calculated by RF was significant high (Roy and Bari, 2022). Results also showed that the relationship between MNDWI and LST was different from that of most studies. Comparing with the studies of Roy and Tetali on land cities (Tetali et al., 2022; Yao et al., 2022c), their studies suggested a negative correlation between MNDWI and LST, while this study was on the contrary. In autumn and winter, MNDWI and LST of island cities were positively correlated. This was mainly related to the characteristics of island cities. Xiamen Island is surrounded by sea on all sides, since the reflectivity of seawater to solar radiation is the lowest among all land use types, the LST of surrounding areas was higher than those areas away from seawater. The sea breeze can extend the thermal benefit due to the albedo increase to urban areas. Meanwhile, the refraction effect of seawater on the sunlight is another main reason for increasing LST in the surrounding areas (Falasca et al., 2022; Ottaviani et al., 2019). Affected by island cities' urban management and control of the coastal buildings in Xiamen Island, most of blocks have lower building height with higher density, which signify the effect in CL city types. As mentioned above, these types of urban blocks also have poor temperature dispersion effect.

In the analysis of 3D urban morphology factors, our results showed a significant positive correlation between SVF and LST at all UBTs in Xiamen Island. SVF is a key factor affecting urban surface heat balance, micro-scale air circulation and atmospheric pollutant diffusion (Miao et al., 2020). The contribution value of SVF calculated according to RF was low in summer (relative to other seasons) due to the high summer temperature of Xiamen Island, and the ground surface received more direct solar radiation. The contribution value of SVF in low-density cities is higher than that in high-density cities due to the higher anthropogenic heat, lower ventilation performance, lower green infrastructure (Kim et al., 2022). This result is consistent with Lai's research (Kim et al., 2022; Lai et al., 2021). The higher the SVF, the worse the radiation shielding effect between buildings, resulting in higher LST. On the contrary, BF and SVF have opposite effects on LST. With the increase of BF, the height difference between buildings has a certain shielding effect on buildings, and the well-arranged buildings also increase the permeability of the block, which is conducive to the evacuation of heat in the block. The height difference of the building also has a great impact on the gas flow in the street canyon, which causes the reduction of LST (Lai et al., 2021; Li et al., 2021). The negative correlation between FAR and LST indicates the release of the space available for greening in the block with the improvement of FAR, and the canyon effect brought by high FAR will improve the ventilation effect of the block, facilitate the evacuation of hot gas, and reduce the LST of the city (Yao et al., 2022a). The LST is higher in summer, so the airflow formed is stronger, and FAR's contribution was also showed the highest in summer. The contribution value of CH was the highest, which also confirms that high-rise buildings can not only cast more shadows to reduce the air temperature in the shadow area but also improve the surface roughness, thus generating mechanical turbulence to reduce urban LST.

4.3. Urban planning implications

Under the background of global warming and rapid urbanization, it is important to alleviate the urban thermal environment and improve

the living environment of urban residents. However, it is difficult to provide scientific suggestions for urban planning merely from a global scale and 2D perspective. Based on the perspective of block scale, the study analyzed the seasonal impact of 2D and 3D urban morphology factors of different UBTs on urban LST through the RF regression model. It provided a relatively complete description and analysis of the thermal environment characteristics between different urban blocks, and reasonably establishes the relationship between LST and UBTs, which can support the mesoscale study of urban thermal environment. In addition, by analyzing the LST and UBTs of island cities, we can also see that compared with land cities, island cities are still affected by the marine environment. Especially for island cities with a high level of urbanization, such as Xiamen Island, more attention should be paid to the marine environment and urban morphological characteristics to alleviate the heat island effect of island cities (Zhang et al., 2022c; Zhu et al. 2021). Scientific urban planning, renovation of old areas and expansion of green space are also promoting the stability and improvement of the ecological quality of Xiamen Island (Liu et al. 2021). Our research findings have several implications for the future urban construction. First, for the urban blocks to be constructed or transformed, in addition to considering the needs of urban development, we should also pay attention to the preservation of urban green space, and plan the urban green space system in advance to better improve the cooling benefits of NDVI (Yao et al., 2022b). Second, for the set of blocks, a reasonable range should be established according to the FAR of the city, and the internal building structure can have certain changes, with a certain BF, to avoid higher SVF, so as to better improve the shielding effect of buildings and reduce the LST of the city. (Kim et al., 2022) Third, the construction of island cities and land cities cannot be generalized, and urban planning and construction should be carried out according to their particularity.

4.4. Limitation and prospects

This study used the 2D and 3D urban morphology factors analysis to analyze the seasonal variation of LST in different urban types, and the results and findings can provide a good reference for the construction and development of island cities. Nonetheless, there are still some limitations in this research. First, although we selected remote sensing images of four seasons with similar weather conditions to analyze the LST of Xiamen Island in four seasons, we only picked one for each season, which might cause some errors. Second, the study only evaluated the changes of LST during the day, and the changes of LST at night in island cities were not examined. Third, the LST of Xiamen Island might be affected by urban functional zoning, and different urban functional zoning could lead to different LST. Fourth, the research only focuses on the urban composition of Xiamen City, and less consideration is given to the factors of urban configuration. Therefore, in a future study, we would consider multi-source data analysis and compare the change characteristics of LST at night in land and island cities, so as to provide more reference for the construction of island cities.

5. Conclusion

This study selected Xiamen Island as a typical island city to analyze the seasonal impact of different UBTs on urban LST. We focused on evaluating the correlation and contribution of 2D and 3D urban morphological characteristics of different block types to LST, and summarizing the seasonal relationship between UBTs and LST of island cities. The key conclusions of this study include are summarized below. First, similar to land cities, CL has a higher LST in various types of blocks in island cities regardless of the season. Second, NDVI is the main factor for cities to reduce LST, especially in summer, while NDBI is the opposite. Third, different from land cities, we found a positive correlation between MNDWI and LST in autumn and winter, which is mainly affected by island cities' urban management and control of the coastal

buildings and high-water specific heat capacity. Fourth, in 3D factors, BD and SVF showed a significant positive correlation with LST. The higher the SVF, the worse the radiation shielding effect between buildings. The higher the BD is, the more crowded the building is, and the space available for greening is lower, resulting in higher LST. Fifth, the higher the BF, the better the shading effect caused by the building height difference. The LST of island cities was studied at the block scale. The results can assist urban planners and decision-makers to understand the thermal environment of island cities, and provide a reference for them to formulate scientific and reasonable planning.

CRediT authorship contribution statement

Zhipeng Zhu: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition. **Yuanping Shen:** Resources, Formal analysis, Visualization, Project administration. **Weicong Fu:** Methodology, Investigation, Visualization. **Dulai Zheng:** Investigation, Data curation. **Peilin Huang:** Investigation, Data curation. **Junyi Li:** Investigation, Data curation, Writing – review & editing. **Yuxiang Lan:** Investigation, Data curation, Writing – review & editing. **Ziru Chen:** Investigation, Data curation. **Qunyue Liu:** Methodology, Investigation. **Xiaoling Xu:** Methodology, Investigation. **Xiong Yao:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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