Investigation of The Impacts of Urban Morphology On Summer-Time Urban Heat Island Using GIS And Field Measurement

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Abstract

This study investigates the relationships between urban morphology and summertime urban heat island in Hong Kong. A total of 33 urban design parameters describing complex high-rise high-density urban morphology are proposed and categorized into three groups, i.e., land-use intensity, built form, and space enclosure. A process combining the python script and the geoprocessing function is proposed to quickly calculate the morphological parameters for 10 sites and 160 points. Microclimate data were collected using onsite measurement equipment. Pearson correlation and multiple linear regression analysis are conducted to quantify the impact of each parameter on urban heat island (UHI) intensities at 3 pm (UHI_3pm) and 9 pm (UHI_9pm). 16 parameters are found to be statistically correlated with UHI_3pm and 9 parameters with UHI_9pm. Results show land-use intensity parameters have the highest correlation with UHI, followed by built form parameters and then space enclosure parameters. Furthermore, it is found that site-level parameters can better explain UHI variation compared to point-level parameters. This research paves the path for quickly extracting urban morphological parameters and enhances the understanding of the impact of complex high-rise high-density urban environment on summertime UHI. The results can inform policy makers with the guidelines to create more comfortable urban environment.

1. Introduction

The process of urbanization has created heterogeneity of thermal mass, surface roughness, albedo, etc., which alter the microclimate condition in the urban environment. For example, a large difference in air temperature can be found between urban and rural areas, which is known as the urban heat island (UHI) phenomenon¹. UHI is caused by the change of thermal balance in the urban environment, such as higher solar radiation absorption and heat storage by the urban structure, higher anthropogenic heat emission by intensified human activities, and less heat loss due to the wind sheltering effect by urban constructions². According to previous research, UHI leads to an increase of thermal stress in summer³, higher risk of heat-related mortality^{4,5}, higher energy consumption^{6,7}, and urban air pollution⁸, and thus become an alarming threat to the human being.

Urban planning and design response to urban microclimate is the key to creating a sustainable urban environment, which requires a thorough understanding of the correlation between urban microclimate and urban design. Over the past hundred years, UHI as an indicator of urban microclimate has been extensively investigated all over the world^{1,2,9-12}. Urban morphology is generally regarded as one of the most important factors of the UHI intensity¹³⁻¹⁵. It refers to the physical features of urban buildings at the local or district scale, such as the dimension of the buildings and the spacing, street design, land use, urban density, etc. They affect UHI by regulating solar radiation availability, thermal reflectivity, and wind flow pattern in the urban environment².

To quantitatively investigate the influence of urban morphological features on climate variations, multiple urban planning and design parameters have been correlated with climate factors (Table 1). These parameters are categorized into 3 groups, including land use intensity, built form, and space enclosure¹⁶. The effect of these features on UHI varies in different urban contexts and climate conditions. The

applicability of these parameters on the climate research in different area may also vary. Hong Kong, as a typical high-rise high-density city, exhibits a high level of complexity in the building layout. It has a population of over 7 million living within only 270 km² of built-up area. This extremely dense population has shaped Hong Kong into a unique high-rise high-density urban environment. The general research output from other areas may contribute to the understanding of the UHI effect in Hong Kong but cannot directly guide the urban planning and design practices. Many of the morphological parameters from previous research are more suitable for homogeneous urban form, since they cannot reflect the detailed design features of highly diversified building arrangement. Therefore, to better parameterize the complex high-rise high-density urban environment in Hong Kong, new parameters shall be explored.

Table 1
Urban morphological parameters that influence urban climate in previous research

Category	Parameters
Land-use intensity	Building density ¹⁷⁻¹⁹ / building cover ratio ²⁰
	Floor area ratio ^{12,19} / Rugosity ^{18,21}
	Mineralization factor ¹⁸
Built form	Average building height ²²
	Building height variation ^{23,24}
	Height to floor area ratio ^{25,26}
	Compacity ¹⁸
	Complete aspect ratio ²⁷ / Building envelope area to site area ratio ²¹
	Total building volume to the number of buildings ratio ^{21,24}
	Building volume to site area ratio ²¹
Space enclosure	Canyon aspect ratio (building height / street width) ^{13,28-35}
	Street aspect ratio (building length / building height) ^{18,28}
	Sky view factor ³⁶⁻⁴⁰
	Frontal area density ⁴¹
	Urban porosity ¹⁸

This study aims to investigate the relationships between UHI and urban morphology of high-rise high-density urban environments like Hong Kong. Important urban morphological parameters that influence UHI would be identified by analyzing both newly proposed and existing parameters. Value of parameters are calculated from 160 points and 10 sites in real high-rise high-density urban settings where microclimate

measurements are conducted. Statistical analysis will be conducted to find the correlation between UHI and different morphological parameters. Empirical models will be developed to help explain spatial UHI variation in the highly heterogeneous high-rise high-density urban environment. The research outcome would enhance the understanding of parameterizing complex high-rise high-density urban environment and serve to inform urban planners and designers with scientific information on climate-sensitive design strategies.

2. Identification Of Urban Morphological Parameters

Urban morphology has a strong impact on UHI, which has attracted increasing research interests. Table 1 lists the urban morphological parameters proposed by previous research. It can be seen that the design features described by some of the parameters overlap with each other. This research combined the previously-proposed and newly-proposed parameters to better capture the complex morphological characteristics of high-rise high-density urban environment. The urban morphological parameters for this study are chosen and proposed based on the following principles:

- can be controlled and understood by urban planners and architects;
- can properly address the 3-D characteristics of urban morphology, which can give urban planners and architects an intuitive sense of physical structure at the conceptual design stage;

To verify the effect of different scales of urban morphology on UHI, two levels of variables are proposed in the current study, including site-level and point level variables. For the site-level parameters, the data within the whole research site (400 m×400 m) were collected. For the point-specific parameters, the data within an area with a radius of 30 m were collected^{11,12,42}. Based on the criteria mentioned before, the following 3 groups of parameters are proposed, including land-use intensity, built form, and space enclosure (Table 2).

Table 2
3 groups of parameters

Parameters	Abbreviation	Description	Level	Source
land-use intensity	ParkArea	The area of each park	Site	43
	FAR_St	The floor area ratio of all the buildings	Site	12,19
	FAR_Pt		Point	12,19
	FARtow_St	The floor area ratio of the towers	Site	New
	FARtow_Pt		Point	New
	FARpod_St	The floor area ratio of the podiums	Site	New
	FARpod_Pt		Point	New
	DENSITYbot_St	Building density at the height of 10 m	Site	20
	DENSITYbot_Pt		Point	20
	DENSITYmid_St	Building density at the height of 30 m	Site	New
	DENSITYmid_Pt		Point	New
	DENSITYtop_St	Building density at the height of 60 m	Site	New
	DENSITYtop_Pt		Point	New
built form	H_St	Average building height	Site	22
	H_Pt		Point	22
	HV_St	Building height variation	Site	23,24
	HV_Pt		Point	23,24
	H/FA_St	Average building height to floor area ratio	Site	New
	H/FA_Pt		Point	New
	SAR_St	Building surface area/site area	Site	New
	SAR_Pt		Point	New
	COMP_St	Exterior building surface area divided within the whole site	Site	18
	COMP_Pt		Point	18
space enclosure	SVFall_Pt	Regular sky fraction	Point	39
	SVFbld_Pt	Sky fraction that formed only by the surrounding buildings	Point	New

Parameters	Abbreviation	Description	Level	Source
	SVFe_Pt	Regular sky fraction on the east side	Point	New
	SVFw_Pt	Regular sky fraction on the west side	Point	New
	SVFs_Pt	Regular sky fraction on the south side	Point	New
	SVFn_Pt	Regular sky fraction on the north side	Point	New
	ARn_Pt	The aspect ratio on the north side	Point	New
	ARe_Pt	The aspect ratio on the east side	Point	New
	ARs_Pt	The aspect ratio on the south side	Point	New
	ARw_Pt	The aspect ratio on the west side	Point	New

2.1. Land-use intensity group

In this group, a total of 13 parameters that address land-use intensity are proposed (Table 2). Park area (ParkArea) was calculated based on the green open space bounded by the surrounding buildings to fully capture the morphological size of the open space. Floor area ratio (FAR) and building density have been widely used to control the construction intensity in urban design. To fully address the complexity of real urban fabrics in Hong Kong, variants of FAR and building density are proposed to describe the amount of building area at different vertical levels on the site and point scales According to Building (Planning) Regulations (Chap. 123F of Hong Kong Legislation), the site coverage for a non-domestic building, or for the non-domestic part of a composite building, on class A, B, or C site may, whatever the height of the building, reach 100% to a height not exceeding 15 m above ground level. Under this regulation, a “tower + podium” building form has been the predominant type in Hong Kong. It has a giant podium at the bottom and high-rise towers above, which is called “birthday cake building” locally. Therefore, it is necessary to distinguish between the podium and tower parts by calculating the FAR value for each respective part (FARpod and FARTow). As FAR is defined as the total floor area divided by the site area, FARpod and FARTow represent the total podium area and tower area divided by the site area respectively.

Building density refers to the ratio of building footprint to total land area. Building density describes the two-dimensional feature of intensity, while FAR the three-dimensional feature. A similar approach was adopted to calculate building density at three levels, covering the bottom, middle, and top level due to the high variation in building heights in Hong Kong. Based on the data from 10 research sites, it was found that the average building height is 40 m. Given the 15 m height limit for podiums in Hong Kong, building density was calculated at 10 m, 30 m, and 60 m height levels (Fig. 1a).

Based on the above description, FAR and building density at the site level can be calculated according to the following equations:

$$FAR = \frac{\sum_i^n \text{building_}A_i \times F_i}{\text{site_}A} \quad (1)$$

$$Density = \frac{\sum_i^n building_A_i}{site_A} \quad (2)$$

where represents the floor area of the buildings at a certain height, represents the total area of the site which is 160,000 m² in this study, represents the number of floors for certain buildings.

2.2. Built form group

Building height restrictions are commonly applied in urban planning. Three parameters related to building height, i.e., average building height (H), height variation (HV), and average height to floor area ratio (H/FA) at different levels were calculated (Table 2). HV is represented by the standard deviation of building heights. Building surface area highly influences energy and heat exchange between the buildings and the air, which makes it a proper index in evaluating the climatic impact of building form. The ratio of building surface area to site area (SAR_St, SAR_Pt) and Compacity (COMP_St and COMP_Pt) were calculated in this study. Compacity is calculated as exterior building surface area divided by building volume, which can assess the urban compactness and capacity^{18,21}. These two parameters help to evaluate building mass and its heat storage and release ability.

2.3. Space enclosure group

The correlation between Sky View Factor (SVF) and outdoor climate has been verified in many studies^{37–41}. But it cannot provide urban designers with enough detailed suggestions on climate-sensitive design, since a certain SVF value does not represent a specific type of urban building layout. There might be a variety of sky fraction shapes that share the same SVF value. SVF cannot precisely define the heterogeneous urban morphology as the relation between the sun's path and the sky fraction is not addressed. In this study, attempts were made to decompose SVF to capture the enclosure degree of surrounding buildings from four directions and also to distinguish the influence from buildings and vegetation (Fig. 1b). Therefore, six parameters were proposed, covering SVFall_Pt, SVFbld_Pt, SVFe_Pt, SVFw_Pt, SVFs_Pt, and SVFn_Pt (Table 2).

Street canyon aspect ratio affects the net radiation and stored solar flux of the street. It is generally defined as building height to street width ratio in a highly simplified urban canyon model. In real environments, there may be large variations of building heights between adjoining buildings, while the street orientation may not be parallel to east-west or south-north directions. This poses difficulty in calculating aspect ratio in the real environment since it is hard to determine the building height and spacing. In this study, a new approach was proposed to calculate the aspect ratio. To reflect the actual relation between the measurement point and surrounding buildings, four parameters were introduced to quantify the ratios in four directions. Instead of a single building height, the average height of buildings within the 90 degrees range was employed (Fig. 1c).

The width is denoted by the distance between the measurement point and the building instead of the distance between the buildings in the opposite directions.

3. Methodology

To quickly calculate 33 morphological parameters in 160 points and 10 sites, an automatic process combining the python script and Geographical Information System (GIS) model was introduced. These parameters were then correlated with UHI data ^{24,44,45}. In general, the study was conducted by the following steps:

- ☒ conducted field measurements to collect microclimate data and morphological information in 10 selected sites;
- ☒ built GIS model of study sites by ArcGIS and calculated urban morphological parameters using python script and geoprocessing functions;
- ☒ conducted Pearson correlation and multilinear regression analysis between UHI and urban morphological parameters. proposed empirical models to indicate their relationships.

3.1. Site identification

In terms of site selection for microclimate measurements, the influence of geographic condition, seasonal and weather variance, artificial heat sources shall be well controlled ⁴⁶. Geographic location determines the regional climate background and the distances from cool resources, including sea surfaces and vegetated mountains. For seasonal and weather influence, the climatic condition (temperature, humidity, solar radiation, precipitation, wind, and cloud cover) changes between different seasons and even different days, which could impose significant effects on UHI patterns. To reduce the geographic impact, study sites were carefully selected in the adjacent area on the northern side of Hong Kong Island. Meanwhile, to minimize the seasonal and climatic impact, the measurements were conducted on clear sunny days in the summertime. Originally there were 12 sites with typical urban form investigated, but only 10 sites are analyzed in this study (Fig. 2a). In the preliminary analysis, it was found that the data collected from Sung Hing Lane site (SHL) and Lockhart Road site (LhR) may not be representative due to the difference of measurement time at SHL and land use type at LhR. The other 10 sites were all residential blocks and measured in the months between July and early September, which were typical summer months in Hong Kong. Thus, SHL and LhR are excluded from the present analysis.

In urban climate research, it is important to define the site boundary according to research scales. In this study, it was decided based on a review of different kinds of research on urban morphology and environmental performance, covering main research methods (remote sensing, simulation, and field measurement). In a study of the cooling effect of green space based on remote sensing technology, a size of 240 m × 240 m upon satellite images was employed by Kong et al. to calculate landscape metrics ⁴⁷. In a

physical simulation study on urban bioclimatic design strategies, Sad de Assis and Barros Frota built a scaled 500 m × 500 m model representing an area of 25 hectares ⁴⁸. In a field measurement research project, Krüger and Givoni measured the temperature of seven areas in Curitiba, Brazil, each with a diameter of 250m ⁴⁹. Santamouris ², Edussuriya et al. adopted the area size of 200m × 200m and investigated 20 different urban residential areas to study the relationship between urban morphology and air quality in Hong Kong ²⁴. Based on the six generic urban forms proposed by Leslie Martin and others to address land-use characteristics, Ratti et al. reassessed the environmental performance of these forms using computer analysis techniques, adopting an area size of 250m × 250m ⁵⁰. In the research on the relationships between building energy consumption and urban texture, urban areas with dimensions of 400m × 400m were adopted to extract building form data by using a computer-based image processing technique ⁵¹. Based on the aforementioned studies, a size of 400 m × 400 m was proposed for the research sites in the present study considering the following aspects:

- The cooling effect of green space may extend beyond the site, as far as the park's width ⁵².
- According to the technical circular of Hong Kong Air Ventilation Assessment ⁵³ the surrounding area of up to a perpendicular distance of 2H (highest building in the site) from the project boundary must be included for investigating wind performance. Since building height in the measurement area could normally reach 100m, a 400m × 400m rectangular area was proper for this study.

3.2. Microclimate measurements and field survey

The microclimate measurements in these 10 sites were conducted during three summers from 2010 to 2012. HOBO weather stations were used to record the climate data, with all the sensors installed at the heights ranging from 1.2 to 2 m. There were 160 points measured in total, with 81 points located inside the parks and 79 points on the surrounding streets. The control point in each site was continuously measured and the other points were measured by mobile equipment (Fig. 2b). Microclimate measurements were conducted for 3 days in each site. In each day, the measurements at all points were carried out once every two hours from 1 pm to 9 pm. The microclimate data collected at 3 pm and 9 pm are analyzed in this paper, representing the hottest period during daytime and early nighttime. More details on the field measurements and climatic data were presented in the previous paper ¹⁹.

Urban building information and land use data were collected through on-site surveys combined with the information from GoogleMaps, and GeoInfo Map provided by Survey and Mapping Office/ Lands Department, HKSAR. Fish-eye lens pictures at all measurement points were taken to calculate SVFs. The urban morphological information including terrain, building layout, greenery, and measurement points was consolidated into the ArcGIS models.

3.3. Parameter calculation by ArcGIS

By collecting the morphological data of all the sites, 10 GIS models with building form, area, height, and volume information were built in ArcGIS. A systematic process was established to calculate the design parameters at both site and point level:

- Firstly, geoprocessing functions such as “Buffer”, “Intersect” etc. were used to select the buildings to be included in the calculation according to a certain site or point.
- Then, Python scripts were written to calculate specific parameters such as DENSITY and HV using either mathematical function built-in Python or Data processing tools in ArcGIS.
- Finally, the model function in ArcGIS was used to combine these steps to calculate the parameters proposed in Sect. 2.

Figure 3 shows the schematic workflow configuration to calculate aspect ratio for each point in the “Model” interface and the lines created for getting the 1-degree resolution in aspect ratio (AR) calculation.

3.4. Data analysis

Pearson correlation and multiple linear regression analysis were conducted to quantify the impact of each parameter and to develop empirical models that explain the UHI variation. In the regression analysis, dependent variables are the UHI intensities at 3 pm and 9 pm (UHI_3pm and UHI_9pm), while independent variables are the morphological parameters identified in the last section. For dependent variables, UHI is defined as the difference between the measured air temperature at each point and the data from the rural area weather station (Ta Kwu Ling weather station). Ta Kwu Ling weather station has been widely used by researchers in Hong Kong as a rural site ^{54,55}.

To identify important urban morphological parameters, Pearson correlation was conducted between UHI_3pm and UHI_9pm with all parameters. Only those parameters proven to be statistically correlated with UHI intensities will be considered in the multiple linear regression.

Multicollinearity problems may exist in such a large quantity of independent variables. This problem was carefully dealt with through two main steps. Firstly, Pearson correlation was carried out to examine the correlation coefficient between every two design parameters. A coefficient higher than 0.80 indicates high collinearity, which means these two parameters cannot exist in one model. Secondly, based on the first step, models with a different combination of independent variables can be generated. Some scholars have suggested a formal detection of tolerance for these models to avoid multicollinearity ⁵⁵. In this study, a tolerance of less than 0.10 was considered as a collinearity problem. The final models were obtained by removing the independent variables with a tolerance lower than 0.1 and P-value higher than 0.05.

4. Results

4.1. UHI at 3 pm and 9 pm

Figure 4 presents the UHI intensities of all sites at 3 pm and 9 pm. It can be seen that UHI intensities at 9 pm are much higher than 3 pm. The UHI at 9 pm is around 3 °C, with a very small fluctuation among all sites.

The minimum is 2.23 °C at the WOL site and the maximum is 3.84 °C at the TWS site. As for 3 pm, the UHI intensities vary substantially among these sites. Cool island effects are discovered in 5 sites, with the air temperature at these sites being lower than rural weather stations. The minimum is -1.53 °C at the CS site and the maximum is 2.34 °C at the TS site.

4.2. Calculation results of design parameters

The descriptive data of all 33 morphological parameters are presented in Table 3. Figure 5 displays 5 site-level and 1 point-level parameters with more details. It can be seen that density decreases from bottom to top. Densities at the bottom level (10 m above ground) are between 0.31–0.49 with an average value at 0.39, while the middle-level densities (30 m above ground) are mainly between 0.12–0.23 and the top-level densities (60 m above ground) are around 0.11. It reflects the characteristic of the typical “podium + tower” urban building form, which has a large building mass at the ground level and slender buildings above. Figure 5b shows that except for TS site (3.98), the total FAR values of all sites are above 4, with the highest value at KUF site being 7. The podium level FAR values range from 0.69 to 1.69, while the tower level from 3.23 to 5.49. These sites represent typical high-rise high-density urban form in Hong Kong. The average building height of all sites is around 40 m, with the highest value being 52.81 m at TWS site. Except for KUF and WOL sites, the other sites share a similar average building height of around 40 m. SAR_St values of all sites range from 3.70 to 5.27. It is worth mentioning that SAR_St shows a similar trend as FAR_St, which indicates possible collinearity among these two parameters. Also the measurement points are highly enclosed by surrounding buildings with average SVFall_Pt being 12.3%. The 95% confidence interval is from 11.5–13.3%.

Table 3
Descriptive statistics of all design parameters

	Min	Max	Mean		Min	Max	Mean
ParkArea	754.6	7502.5	2430.7	H/FA_St	1.96	3.02	2.47
FAR_St	3.98	7.00	5.59	H/FA_Pt	0.09	0.47	0.21
FARpod_St	0.69	1.69	1.13	SAR_St	3.70	5.27	4.48
FARtow_St	3.23	5.49	4.45	SAR_Pt	0.02	4.59	2.18
FAR_Pt	0.09	5.39	2.07	COMP_St	0.75	0.97	0.81
FARpod_Pt	0.00	1.06	0.41	COMP_Pt	0.07	9.58	1.23
FARtow_Pt	0.07	4.54	1.66	SVFall_Pt	0.00	0.30	0.12
DENSITYbot_St	0.31	0.49	0.40	SVFbld_Pt	0.00	0.43	0.17
DENSITYmid_St	0.12	0.23	0.19	SVFe_Pt	0.00	0.63	0.21
DENSITYtop_St	0.07	0.17	0.11	SVFw_Pt	0.00	0.89	0.24
DENSITYbot_Pt	0.00	0.51	0.19	SVFs_Pt	0.00	1.00	0.22
DENSITYmid_Pt	0.00	0.19	0.06	SVFn_Pt	0.00	0.78	0.17
DENSITYtop_Pt	0.00	0.14	0.05	ARn_Pt	0.84	47.61	4.98
H_St	34.34	52.81	40.16	ARe_Pt	0.68	66.32	5.02
H_Pt	9.63	75.00	28.89	ARs_Pt	0.68	35.15	4.30
HV_Pt	1.30	40.89	20.44	ARw_Pt	0.71	35.48	4.14
HV_St	25.98	37.05	30.96				

4.3. Pearson correlation

Figure 6 shows the results of the Pearson correlation between UHI_3pm and UHI_9pm with all design parameters. It is found that 16 out of 33 parameters are correlated with UHI_3pm and 9 parameters are correlated with UHI_9pm. Among 3 groups of morphological parameters, land-use intensity parameters have the highest correlation with UHI, followed by built form parameters, while space enclosure parameters have the lowest correlation.

For the land-use intensity parameters shown in Fig. 6a, the site-level parameters exhibit a much higher correlation with UHI intensities than the point-level parameters. Strong negative relations are found between the site-level FAR and density with UHI_3pm. This can be explained by the shading effect provided by the podium and towers. In the daytime, higher construction intensity, meaning larger building mass, could reduce the air temperature in multiple ways. Firstly, it could intercept solar radiation and prevent it from reaching pedestrian levels, which is especially important for a sub-tropical city like Hong Kong. Secondly,

more incoming solar radiation can be reflected by the roofs since the surface albedo of roof material is normally higher than road pavement. Lastly, building mass can absorb and store more solar heat than the rural area, where solar radiation is either reflected directly or absorbed and later emitted in a short time to heat up the air during the daytime. Smaller correlation can be found between FAR_St, FARtow_St, and DENSITYbot_St with UHI_9pm. It may be explained by the fact that more anthropogenic heat are released into the air during early nighttime in these residential blocks. Among the land use intensity parameters, FAR_St and DENSITYbot_St have the highest correlation coefficients with UHI_3pm. It suggests that in complex high-rise high-density urban environments, conventional morphological parameters such as FAR and density are most influential for UHI variations. Park area is found to be positively related to UHI_3pm and UHI_9pm. Larger parks mean more solar radiation due to less shelter from surrounding buildings. It suggests the importance of shading in Hong Kong to ameliorate outdoor thermal stress in the afternoon and early nighttime.

For the point-level parameters in the built form group shown in Fig. 6b, H_Pt is found to be positively correlated with UHI_3pm and UHI_9pm, while all the other point-level parameters do not have a statistical correlation with UHI. A similar positive correlation is found for H_St with UHI. This indicates increasing building height for high-rise high-density cities may aggravate the UHI intensity. On the other hand, no statistical relation can be found between height variation (HV_St) with either UHI_3pm or UHI_9pm. This may be caused by the adverse effects of height variation on UHI, such as improving urban ventilation to remove excessive heat and lowering overall surface albedo to absorb more solar radiation. A negative impact is found for SAR_St to both UHI_3pm and UHI_9pm. The result suggests increasing building surface area may lower outdoor air temperature. The features addressed by this parameter may be overlapped with FAR to some extent, since it can also reflect the amount of building mass. The collinearity problem between SAR_St and FAR should be carefully examined in multiple regression analysis.

Compacity (Comp_St) is calculated as the total exterior building surface area divided by the total building volume within the site. Higher Comp_St means more surface area with the same building volume, resulting in more radiation absorbed by exterior walls during the daytime, and more surface to release heat at night. Theoretically, higher Comp_St would lead to higher UHI in the daytime and lower UHI in the nighttime. However, in this study, Comp_St is found to be positively related to both UHI_3pm and UHI_9pm. The possible explanation for its positive impact on early nighttime may be either due to the delayed heat release or the excessive heat absorption during the daytime.

For the space enclosure parameters as shown in Fig. 6c, 4 out of 10 parameters are statistically correlated with UHI_3pm, while no parameter is related to UHI_9pm. It is found that SVFall_Pt (regular SVF) is positively related to UHI_3pm, which is in line with the general theory. Higher SVF means more solar radiation can reach the ground and building walls, which increases heat gain. It suggests SVF should be well controlled especially in sub-tropical cities, where solar shading is critical for reducing thermal stress. To distinguish the shading effects from the buildings and vegetation, SVFbld_Pt is calculated and analyzed as well. But the result shows that it cannot explain the UHI variation, which means vegetation plays an important role in providing shading at the point level. Also, it is found that SVFe_Pt, SVFw_Pt, and SVFs_Pt have a positive influence on UHI, while no correlation between SVFn_Pt and UHI can be found. According to the sun path on

sky view images (Fig. 1b), only the sky fraction on the east, west, and south directions would affect the incoming solar radiation into the urban canyon. It means the sky fraction related to the sun path has a stronger impact on heat gain. On the other hand, no statistical correlation can be found between SVF related parameters and UHI_9pm, and between the aspect ratio related parameters and UHI during both daytime and early nighttime. It suggests that for the high-rise high-density urban environments like Hong Kong, the proposed calculation method for aspect ratio still cannot properly capture the morphological feature.

4.4. Regression analysis

To deal with the collinearity problem, Pearson correlation was conducted among 17 independent variables that are statistically correlated with UHI_3pm or UHI_9pm to check the relation with each other (Fig. 7). Collinearity is confirmed when the correlation coefficient between two variables is higher than 0.8 (marked with black dots). It is found that the correlation among FAR_St, FARpod_St, FARTow_St, DENSITYbot_St, DENSITYtop_St, and SAR_St are quite high, indicating that these parameters cannot be included in one multiple regression model. This is because these design parameters address similar design features from different scopes. The correlation coefficients of these parameters with UHI are higher than other parameters, which suggests that they are the most important parameters in each regression model.

Stepwise multiple regression was conducted to explore empirical models for explaining UHI_3pm and UHI_9pm respectively. Regression models are selected based on the following standards: (1) significance level is smaller than 0.05; (2) tolerance value is higher than 0.1; (3) variance inflation factor (VIF) value is smaller than 10; (4) Pearson correlation coefficient between every two variables is smaller than 0.8; (5) the impact of all parameters agree with the Pearson correlation results in the last section; (6) the R square value of each model is larger than 0.5. The regression results for UHI_3pm and design parameters are presented in Table 4, including 5 models with the R square ranging from 0.572 to 0.711. From the above criteria, no suitable model can be established for UHI_9pm. The Pearson correlation results show that only 9 design parameters are statistically related with UHI_9pm with relatively lower coefficients. It suggests the early nighttime UHI variation in high-rise high-density residential blocks is influenced by much more complex conditions aside from urban morphological design features.

It can be seen from Table 4 that land-use intensity parameters have a higher influence on UHI than other parameters. Model 1 shows that FAR_St has a negative relation with UHI_3pm while H_St and SVFw_Pt have positive impacts on UHI_3pm. If FAR_St increases from 5 to 6, UHI_3pm would decrease by 0.759 °C. H_St appears in 3 models, indicating that if H_St increases by 10, UHI_3pm would increase by 0.27 °C-0.42 °C. Model 2 shows an increase of 1 for FARTow_St would lower UHI_3pm by 0.818 °C. Model 3 and 4 have the highest R² as 0.711 and 0.693, which both include DENSITYbot_St as the leading variable. It shows if density at the bottom level increases from 30–40%, UHI_3pm can be reduced by around 1.2 °C. Model 5 shows if SAR_St increases from 4 to 5, UHI_3pm would be reduced by around 1 °C. Model 1, 2, 3, and 5 show that a 10% increase of SVFw_Pt would raise UHI_3pm by around 0.06 °C to 0.08 °C.

Table 4
Empirical models (dependent variable: UHI_3pm)

No	Variables	R Square	B	Std. Error	Beta	t	Sig.	Tolerance	VIF
1	(Constant)	0.635	4.778	1.311		3.644	0		
	FAR_St		-0.759	0.074	-0.805	-10.259	0	0.382	2.617
	H_St		0.033	0.01	0.175	3.312	0.001	0.843	1.186
	SVFw_Pt		0.699	0.245	0.144	2.853	0.005	0.926	1.08
2	(Constant)	0.572	2.443	0.679		3.596	0		
	FARtow_St		-0.818	0.075	-0.65	-10.897	0	0.77	1.298
	H_St		0.027	0.011	0.145	2.487	0.014	0.804	1.243
	SVFw_Pt		0.593	0.262	0.122	2.264	0.025	0.945	1.059
3	(Constant)	0.711	4.682	0.271		17.29	0		
	DENSITYbot_St		-12.169	0.65	-0.808	-18.735	0	0.99	1.01
	SVFw_Pt		0.846	0.21	0.174	4.037	0	0.99	1.01
4	(Constant)	0.693	4.713	0.289		16.309	0		
	DENSITYbot_St		-12.06	0.682	-0.801	-17.693	0	0.954	1.048
	SVFs_Pt		0.561	0.223	0.114	2.521	0.013	0.954	1.048
5	(Constant)	0.624	2.931	0.639		4.584	0		
	SAR_St		-1.068	0.085	-0.652	-12.503	0	0.886	1.128
	H_St		0.042	0.01	0.224	4.327	0	0.902	1.109
	SVFw_Pt		0.835	0.241	0.172	3.463	0.001	0.98	1.021

5. Discussion

According to Pearson correlation, the site-level parameters have a higher correlation with UHI than the point-level design parameters. It means the site-level urban morphology plays a more important role in influencing urban thermal conditions. Moreover, the coefficients of FAR and density parameters with UHI_3pm are the highest among all parameters, which indicates that the land-use intensity parameters at the site level are most influential on summertime UHI in the afternoon. By decomposing FAR and density into different levels, strong correlations are found between decomposed parameters and UHI, but the classical FAR and DENSITYbot still show the highest correlation with UHI.

In this study, building density is negatively correlated with UHI, which is contradicting to a few other studies. Previous studies concluded that increasing building density would lead to a higher outdoor air temperature

since the wind flow in urban areas was blocked²⁰. On the other hand, higher density means less solar radiation can enter into the street canyon. Based on the different results in other area and Hong Kong, assumption can be made that when building density is under a certain level, ventilation plays a dominant role in governing outdoor air temperature, but when building density is higher than that certain level such as in Hong Kong, its shading effect becomes the dominant factor. This exact level of building density can be investigated in future research.

The FAR values of 10 research sites in the present study ranged from 3.98 to 7.00. The regression model shows that an increase of 1 for FAR_St can lead to a decrease of UHI_3pm by 0.759 °C. In an empirical study conducted in Shanghai¹², the same variation in FAR can reduce daytime UHI by only 0.124°C-0.198°C. In that study, the FAR values of most research sites are around 2–3, which is much lower than in Hong Kong. It indicates that daytime UHI is more sensitive to the FAR variation in high-rise high-density cities in subtropical climate zone.

The positive relationship between the park area and UHI should be carefully interpreted for design implications. Suggestions cannot be made that large urban parks should be replaced by small parks. Results from the present study can only help to explain the UHI variation at 3 pm and 9 pm in a high-rise high-density urban environment. It is generally acknowledged that green area provides not only environmental benefits but also social and psychological welfare for the community. Besides, further investigation on comparing the influence of one large park and several small parks is needed.

The positive relationship between Comp_St and UHI suggests that buildings with compact and regular plans are favored considering outdoor thermal environment, which have lower perimeters compared to irregular shapes given the same plan area. The result is not only in line with general theory, but also the energy-efficient building design strategy. Concerning building energy efficiency, the least surface area would be preferred since heat is mainly lost through building envelope. Therefore, the buildings with regular and compact plans will be beneficial for both outdoor and indoor thermal environments.

Many previous studies reported the different effects of urban design on daytime and nighttime UHI^{12,43}. However, it is found in the present study that parameters confirmed to be related with both 3 pm and 9 pm UHI show consistent influence on UHI at two different times. From a report on the difference between urban and rural climate based on the data from Hong Kong Observatory, it is demonstrated that UHI keeps rising from 3 pm to 9 pm until reaches the maximum around 6 am, but the rising rate decreases drastically after 9 pm⁵⁴. It is different from many cities where the UHI maximum occurs several hours after sunset⁵⁶. The authors assume it may be partially due to a large amount of anthropogenic heat release during nighttime in Hong Kong. This can also explain two results in this study. One is the consistent influence of design parameters on both 3 pm and 9 pm UHI, while the other is the lack of effective regression models for 9 pm UHI.

6. Conclusion

This study investigates the relationships between urban morphology and urban heat island in Hong Kong. A total of 33 design parameters, calculated on the site and point levels, are proposed to address land-use intensity, built form, and space enclosure in the complex high-rise high-density urban environment. A process combining the python script and the geoprocessing function is proposed to quickly calculate the morphological parameters for 10 sites and 160 points. Microclimate data of 160 points are collected using onsite measurement equipment. Pearson correlation and multiple linear regression analysis are conducted to quantify the impact of each parameter on UHI intensities at 3 pm (UHI_3pm) and 9 pm (UHI_9pm). This research paves the path of quickly subtracting urban morphological parameters and enhances the understanding of the impact of complex high-rise high-density urban environment on summertime UHI. The main results can be summarized as follows.

- 16 out of 33 parameters are found to be correlated with UHI_3pm and 9 parameters are correlated with UHI_9pm.
- Land-use intensity parameters have the highest correlation with UHI, followed by built form parameters, while space enclosure parameters have the lowest correlation.
- The site-level parameters are better at explaining UHI variation compared to the point-level parameters, which suggests urban planning and urban design should be carefully controlled during the policy making process.
- All site-level FAR and density-related parameters are negatively related with UHI_3pm with the highest correlation coefficients, which suggests that shading effect plays a important role in regulating outdoor air temperature in high density city in the subtropical area.
- Park area is positively related with both UHI_3pm and UHI_9pm, which suggests that larger green space does not necessarily lead to lower air temperature. Delicate design of the green space shall be considered
- The positive relationship between Comp_St and UHI suggests that buildings with compact and regular plans are beneficial for the outdoor thermal environment.
- SVFall_Pt, SVFe_Pt, SVFw_Pt and SVFs_Pt have positive influence on UHI_3pm, which also confirms the importance of shading effect in influencing summertime outdoor air temperature.
- Aspect ratio is hard to define the complex morphological feature in a high-rise high-density urban environment.
- Urban morphological parameters can only explain a small part of early nighttime UHI variation.

7. Limitation And Future Research

Due to the limitation of measurement equipment and time, the study is based on a 3-day measurement campaign on 160 points in 10 high-rise high-density sites. The selection of sample sites makes it impossible

to compare the thermal performance difference between compact urban form and low-density urban form. The empirical models developed in this study are not sufficient in predicting the UHI in other urban design scenarios. For the future research, a yearlong continuous microclimate measurement will be carried out at more points. With more data to be divided into train sets and test sets, machine learning tools can be introduced to train and test the empirical models to generate more accurate models in predicting UHI at different times of the year. Also, aside from air temperature, other meteorological factors, such as wind speed, humidity, and solar radiation, should be considered systematically. To overcome the limitation of empirical study, numerical simulation shall also be adopted in the future.

Declarations

Author Contributions

P. L. conceived and designed the study, conducted all the experiments and wrote the manuscript. D. S. conceived and designed the study, reviewed and revised the manuscript. S. S. Y. L. provided the equipment, reviewed and revised the manuscript. H. Q. helped with the experiments and data analysis.

Competing interests

The authors declare no competing interests.

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Figures

(a)

(b)

(c)

Figure 1

a) Illustration of building density at different height levels; b) Sky view image used to calculate SVF from four directions; c) Illustration of Aspect Ratio calculation.

(a)

(b)

Figure 2

a) 3D views of research sites; b) Measurement plan of Hollywood Road site

Figure 3

“model” configuration for calculating aspect ratio in ArcGIS.

(c)

Figure 4

UHI intensities of all sites at 3 pm and 9 pm

Figure 5

Statistics of a) Density; b) FAR; c) H; d) SAR; e) COMP; f) SVFall of 10 sites.

Figure 6

Pearson correlation of UHI_3pm and UHI_9pm with all design parameters.

Figure 7

Pearson correlation among 17 design parameters to check the collinearity problem.