Analysing the relationship between urban form and urban heat island effect at a city-block scale

Xi Deng\(^1\)*, Shunqian Zhang\(^2\), Phillip Jones\(^1\)

\(^1\) Welsh School of Architecture, Cardiff University, Cardiff, CF10 3NB, UK
\(^2\) Institute of Plateau Meteorology of China Meteorological Administration, Chengdu, 610072, China
* dengx4@cardiff.ac.uk

Abstract. Over the last twenty years China has witnessed rapid urbanisation process. The modification of urban land surface due to urbanisation changes not only affects the geometry of an urban settlement but also its thermal properties, which may give rise to the urban heat island (UHI) effect. Although there has been a large amount of research on mitigation strategies of UHI at the urban scale, there is still a lack of research that concerns the influence of urban geometrical settlement on UHI at a city block scale. Chengdu, a megacity in southwest China, has been chosen as the research subject in this study, to identify the existence of the UHI phenomenon, to measure its magnitude, and to investigate the relationship between UHI and urban design variables, including Floor Area Ratio, Building Coverage Ratio, Green Coverage Ratio, Building Height, Plot-layout Form, and Project Type (function). In this study, urban maps of UHI had been derived from MODIS satellite data for 103 selected projects and 28 urban zones. Correlations were carried out between UHI intensity and urban design variables. The study has developed design guidelines for improving outdoor thermal performance at an city block level. Moreover, a new approach to observe UHI at multi-scales in a long-time period had been conducted, providing a new method to analysis UHI at a city-block scale.

1. Introduction

It has been widely recognized that urban form is closely related to urban sustainability and local climate policy [1][2][3], which plays a significant role in influencing solar access on building façade [4] and altering the thermal properties of urban surface [5], thereby determining the variation of temperature in microclimate and creating the urban climate [6][7], and in specific, causing the urban heat island (UHI) effect. On the other hand, urban form alters the urban wind conditions and determines the pattern of population distribution, and both of the features are critical factors of UHI intensity [8][9]. However, existing literature focuses on the features of UHI at macro scales; research at the city-block level is relatively low. In this study, the high-definition of UHI images obtained from satellite remote sensing was processed and overlaid on the selected 103 sites and 28 urban zones within the city of Chengdu in ArcGIS- a tool of geographic information system (GIS), it investigates the relationship between each design variables and UHI value for each site through long-term observation and data processing.

1.1. Remote sensing satellite imagery
The derived MODIS data of land surface temperature has been widely implemented investigating the UHI effect [9][10][11]. In this paper, the remote sensing data was obtained and processed through the receiving and processing system of DVB-S system broadcasts of China National Satellite Meteorological Center and Huayun MODIS satellite [12]. Ninety-nine days with the clear sky from 2005 to 2010 were selected for observation and data collection.

In order to derive the images of urban heat island, the obtained raw data of remote sensing is processed with the method of Inverse Determination of Surface Temperature- the Split Window Algorithm. This method has been used in previous studies [9] [13], being verified with high accuracy [14]. The calculation process of UHI intensity is according to the equation:

$$\Delta T_s = T_s - T_{smin} \tag{1}$$

Where: $\Delta T_s$ is the UHI intensity ($^\circ$C); $T_s$ is the surface temperature at downtown ($^\circ$C); $T_{smin}$ is the surface temperature at suburbs ($^\circ$C).

Due to the characteristics of UHI, there is a temperature interval with an abrupt change at the urban boundary. Moreover, this pattern of temperature distribution can be applied to locate the ‘real’ temperature boundary between urban and suburban areas, thereby identifying rural temperature. Accordingly, the calculation of surface temperature in suburban areas ($T_{smin}$) is conducted by using this novel automatic extraction method of suburb temperature [12]:

$$\Delta T_s \leq \Delta T_s + m\delta_{\Delta T_s} \tag{2}$$

Figure 1. UHI in summer and winter months ($^\circ$C)
Where: $\Delta T_s$ is the difference of temperature between two belts next to each other (the city core is the first belt); $\bar{\Delta T}_s$ is the mean value of the difference of temperature between belts, $\delta_{\Delta T_s}$ is the standard deviation of the difference of temperature between belt; $m$ is a constant that is usually assigned 3 [12].

Therefore, the raw images in typical summer months (June, July, and August) and winter months (December, January, and February) are grouped and recalculated to produce monthly mean images for each of six months, accordingly (Figure 1). All images are processed with $376 \times 368$ pixel working display ($139.25$ metres $\times$ $139.25$ metres for each pixel), corresponding to the rectangular area of $52,358$ metres $\times$ $51,244$ metres urban region of Chengdu.

1.2. The city and site selection

![Figure 2. 103 sites in Chengdu City Map](image)

Chengdu is located at Chengdu Pain and Sichuan Basin within the region of $102^\circ54\text{E}$ to $104^\circ53\text{E}$ and $30^\circ5\text{N}$ to $33^\circ26\text{N}$. The city has a climate of hot summer and cold winter, and it is humid (above 69% in humidity) in all seasons. The annual rainfall is around 1000 mm (with a monthly value of 110 mm to 230 mm in summer), while the yearly average evaporation is 840 mm to 1100 mm (with a monthly value of 115 mm to 153 mm in summer). The average wind speed is low (around 1.2 m/s) with many cloudy and foggy days in winter. According to Deng’s [15] study, till 2010, the urban core of Chengdu had been shaped with tense urban constructions in the forms of modern concrete high-rise buildings and skyscrapers. In the meanwhile, above $6^\circ\text{C}$ UHI intensity (UHII) has been continuously observed since 1988. However, local research intention has been more focused on the urban macro-scale, which leads to the missing of fundamental and theoretical data about the relationship between planning variables and UHI at a micro-scale. Therefore, studies of quantitative research on correlating multiple parameters of urban form with on-site UHI values are needed, in order to provide theoretical support and database for the practice of planning and designing a city block, whereas the large-scale building group has become the mainstream of the urban development [15].

In this paper, 103 the new-constructing city-blocks were selected as target projects; all projects were completed before 2010. The 103 projects are finely distributed within the area of 3 rings development of Chengdu city (Figure 2). Among the 103 projects, 62 are commercial-residential
mixed, one is office-residential mixed, 30 are residential, and 10 are single commercial in use. Due to the restriction of construction height in an urban area, more than 85% of the target projects are limited below 100 metres height. Only one skyscraper, in the central business district, is constructed greater than 150 metres. Moreover, the site area for the 103 projects varies from 3,000 m² to 356,000 m² with an average area of 30,900 m². More than 50% are built with 30% building coverage ratio. The floor area ratio in three-quarters of all projects is restricted no more than 5. The green coverage ratio reaches 25% for most of the projects. Nearly half of the 103 projects are designed with the enclosed plot, while there are 24 sites are semi-opened.

1.3. Variable selection
There are several control parameters for planning any construction project in China, among which Floor Area Ratio (FAR), Building Coverage Ratio (BCR), Building Height (Height), and Green Coverage Ratio (GCR) are mostly concerned in codes and regulations. Moreover, variables of Project Type and Plot Layout (PL) are restricted accordingly due to the urban planning policies and local codes. Table 1 summarises the six key variables that have been selected in this study. In this study, seven types of functionality are summarized, which are the different combinations of residential, commercial, office, and HOPSCA. Moreover, as shown in Figure 3, the target projects are categorized into five groups: tower, linear, semi-closed, interspersed and court, according to the geometric form.

| Variables                | Abbreviations | Properties                                      |
|--------------------------|---------------|-------------------------------------------------|
| Project Type             | TYPE          | Residential (R), Commercial (C), Office (O), HOPSCA |
| Plot Layout              | PL            | Tower, Linear, Semi-closed, Interspersed, and Court |
| Green Coverage Ratio     | GCR           | The ratio of green area to the total site area  |
| Floor Area Ratio         | FAR           | The ratio of total building floor area to the total site |
| Building Coverage Ratio  | BCR           | The ratio of building ground floor area to the total |
| Building Height          | HEIGHT        | Building height                                  |

1.4. Mapping UHI onto 103 projects and GIS-based (ArcGIS) analysis
Through the Spatial Analysis Tools of the Esri’s ArcMap, the 103 selected sites are symbolised as a shapefile according to their geo-coordinates, and the UHI intensity value within satellite-derived images are input into this tool and are assigned into the different layers, thereby obtaining the mean value of monthly UHI intensity over the target projects.

2. Data analysis
2.1. Mapping Plot Layout vs UHI
According to the plot plan, the projects are categorised into five groups (Table 1): Tower, Linear, Semi-closed, Interspersed, and Court. The result of the mean value of UHI intensity in each type of projects is shown in Figure 4. In general, sites with less openings in terms of plot layout (Interspersed and Court) are recorded lower summer-UHII and higher winter-UHII, while the ‘fully open’ projects (tower) suffer the UHI nearly 0.9°C higher in summer and 0.7°C lower in winter than the projects in more closed plot layout (Semi-closed and Courts). When comparing to the other four types of plot layout, the Tower layout suffers highest summer-UHII (4.45°C) and lowest winter-UHII (1.01°C).

The Interspersed Group, which has multi openings on the plan, inner courtyards, and Interspersed buildings, records the lowest summer-UHII and the highest winter-UHII. It reveals the most appropriate form of plot layout for city blocks in Chengdu in terms of plot layout form of building group with minimum the thermal impacts of building group on outdoor spaces. Moreover, the majority of the building groups with the three types of plot layout (Tower, Linear, and Semi-closed) are located within areas of 5km away from the city centre, and the Interspersed Group is more frequently planned in outer urban areas. Therefore, the location of the buildings has a significant impact on plot layout, which indicates the possible influence of background effect on on-site UHI, which is provided by the surrounding constructions.

The interspersed form is often more homogeneously designed in terms of buildings height, buildings within the group provide over-shading to each other, while this form allows as much openings as possible on the layout of the site to let the breeze take away a considerable amount of heat stored within site generated by high-angle sun in the summertime. The courtyards within the interspersed sites are designed with more significant green area, sometimes even with water bodies, which potentially provide efficient UHI mitigation measures. In the wintertime, the interspersed group benefits from its wide-spread and highly free building settlement to receive and store solar radiation, while wind speed is lower than its annual average (below 1.2 m/s), thereby leading to the highest UHII among all layout forms. However, the towers receive relatively high amounts of solar radiation due to little over-shadowing in summer, resulting in the highest UHII. Moreover, their relatively more compact layout avoids the towers receiving high levels of solar radiation compared to other layout forms with much larger site area. In general, the analysis above explains the different potential causes of UHI in summer and winter across different city blocks.

2.2. Function vs UHI
As stated in section 1.3, four basic uses - Residential (R), Commercial (C), Office (O), HOPSCA (complex with hotel, office, park, shopping mall, convention, and apartment) - consist of different types of combination of project functions. Accordingly, the 103 projects are assorted into seven groups based on their design functions: Residential (R), Residential with 5% Commercial (R(5%)), Commercial (C), Commercial + Residential (C+R), Office (O), Office + Residential + Commercial (O+R+C), and HOPSCA. The most popular forms of dwelling in Chengdu are single residential, and residential with limited commercial (small retails with up to 5% of total building area), while the other five types of developments are more public-oriented, including shopping malls, office, hotels, and the mix of them.

As shown in Figure 5, the projects of single residential are observed to have the lowest summer-UHII (3.9°C) while their winter-UHII (1.5°C) is the highest among all project types. On the other hand, compared to the residential city blocks, the average UHII of the public building types is higher in summer and lower in winter. The project type- Office- records the highest value (5.4°C) in summer and lowest (0.5°C) in winter. Introducing other types of use will alter the on-site UHII pattern. The integration of a 5% portion of commercial buildings raises the UHI-summer and lowers the UHII-winter in the residential building projects. Compared to the single commercial projects, the mix of commercial and residential projects tends to have lower values in summer and higher values in winter. The HOPSCA and Office+ Residence Hotel+ Commercial sites have an average proportion of each building type, which decreases the UHII in both summer and winter when compared to the single office sites.

In general, office project sites suffer highest summer-UHII and lowest winter-UHII among the three types of single functions (other two are residential and commercial). The location of a project determines building type. HOPSCA and Office + Residence Hotel + Commercial are located within city core area of less than 3km away from the city centre, whereas residential types are frequently built in locations more than 6km away from urban core. Lastly, the majority of commercial and office projects are located within the middle areas, between 3km and 6km from the city centre. Projects with office functions are mainly high-rise towers. Their “disadvantageous” layout forms enhance the UHI effect on office sites in winter, while they reduce the solar heat stored in winter, thereby resulting in low winter-UHII.

2.3. Performances of design variables on site and point basis

2.3.1 Floor Area Ratio vs UHI

As shown in scatter plots and correlation figure (Figure 6), FAR is positively related to summer-UHII, while negatively related to winter-UHII. FAR has a significant linear correlation with both summer-
UHII and winter-UHII (significance being regarded as an $R^2$ greater than 5% level [16]). A project with larger FAR tends to suffer from higher summer-UHII and lower winter-UHII in winter. A decrease in a value of 1 FAR will reduce summer-UHII by 0.20°C and will benefit from 0.07°C higher winter-UHII. In general, the distribution of FAR values is relatively uneven: more than two-thirds of the points fall within the range of 1 to 8, which is restricted by the local statues for urban planning in the urban area of Chengdu.

2.3.2 Building Coverage Ratio vs UHII. Figure 7 shows reasonable linear correlations of BCR with average summer-UHII and average winter-UHII. In general, the denser plot in plan raises summer-UHII and lowers winter-UHII. It is estimated that every 0.1 (10%) increase in the value of BCR will increase summer-UHII by 0.26°C. While in contrast, a decrease of 0.1 (10%) in BCR will increase winter-UHII by 0.14°C. The distribution of BCR values is also restricted by local planning policies with certain levels; most projects were designed with the BCR 30%, 35% or 40%.

2.3.3 Greening Coverage Ratio vs UHII. Figure 8 indicates that increasing GCR is an effective way to mitigate UHI in summer months and to rise outdoor surface temperature in winter: an increase of 0.1 in BCR will reduce summer-UHII by 0.34°C, and will raise winter-UHII by 0.17°C.

2.3.4 Building Height vs UHII. Figure 9 indicates that building height has a positive relationship to summer-UHII and a negative relationship to winter-UHII. An increase of 50 meters in average building height of a project will result in raising summer-UHII by 0.48°C and decreasing winter-UHII by 0.19°C.

3. Discussion and conclusions

3.1. Selection of Design specific variables: FAR, BCR, GCR, HEIGHT, PL, and TYPE
In this study, all the correlations of parameters with both summer-UHII and winter-UHII are higher than 5% of the significant level. However, no single variable can independently determine the on-site UHII, which is due to the multi-factor effect to which all variables contribute, as reported by other research [16]. From the results on Floor Area Ratio, the denser plots tend to have a higher summer-UHII and lower winter-UHII. Increasing Green Coverage Ratio and openness in plot layout (less enclosure in plot layout on site) are effective to reduce summer-UHII and to benefit from higher winter-UHII. Both increasing Building Coverage Ratio and Building Height raises summer-UHII and reduces the winter-UHII. Residential projects tend to have lower summer-UHII, and public projects, especially in office projects, tend to have lower winter-UHII. For a given density, a careful mix of buildings of various heights has been previously reported to help improve local ventilation as compared to a homogeneous height setting [17].
3.2. Recommended design strategies of city-blocks in Chengdu

The choice of building density should be based on the overall impact on urban heat island effect. The study shows that the site with higher building density tends to have higher outdoor surface temperature, especially for public (non-residential) buildings. It was found that the taller buildings could provide over-shadowing within a limited range, however, the average outdoor surface temperature of the entire site still increases as the buildings get taller. The choice of plot layout should be considered in relation to the microclimate. The study shows that the building groups with interspersed and court plot layout were achieved with a reduced UHI intensity in summer and increased UHI intensity in winter. The study suggests that the modification of ground surface with greening has a considerable impact on the outdoor thermal environment.

3.3. Summary of the Top-Down process

This Top-Down process carried out in this study is a practical approach to investigate the long-term urban temperature at different scales. In comparison to traditional methods (weather stations), processing the surface temperature through MODIS is a more practical method for research on urban heat island effect [18], which can provide substantial images in a relatively short time. Moreover, due to the high resolutions of the images obtained in this study, the derived LST images not only reflect the general pattern of UHI over the entire city at a macro scale, but also precisely describes the UHI values at micro scales (blocks, streets, and buildings).

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