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Summertime heat island intensities in three high-rise housing quarters in inner-city Shanghai China: Building layout, density and greenery

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ABSTRACT

Shanghai as the largest city in China has been suffering from the ever-worsening thermal environment due to the explosive urbanization rate. As an indication of urbanization impact, urban heat islands (UHI) can give rise to a variety of problems. This paper reports the results of an empirical study on the summertime UHI patterns in three high-rise residential quarters in the inner-city Shanghai. Site-means of UHI intensity are compared; case studies are carried out on strategically located measurement points; and regression analysis is followed to examine the significance of the on-site design variables in relation to UHI intensity. It is found that site characteristics in plot layout, density and greenery have different impacts on UHI-day and UHI-night patterns. Day-time UHI is closely related to site shading factor. Total site factor (TSF) as an integrated measure on solar admittance shows a higher explanatory power in UHI-day than sky view factor (SVF) does under a partially cloudy sky condition. Night-time UHI cannot be statistically well explained by the on-site variables in use, indicating influences from anthropogenic heat and other sources. Evaporative cooling by vegetation plays a more important role at night than it does at day. Considered diurnally, the semi-enclosed plot layout with a fairly high density and tree cover has the best outdoor thermal condition. Design implication based on the findings, with consideration on other important environmental design issues, is briefly discussed.

1. Introduction

Shanghai Metropolis is the largest city of China. Its role as the financial and economic hub for South-Eastern China has been leading to a rapid concentration of the population and construction activities. The population of Shanghai Metropolis increased from 16.1 million in 2000 to18.6 million in 2007 [1]. Because of the elevating population density and limited available land, high-rise apartment building is becoming the mainstream of the residential developments especially in the inner-city area (defined by the Inner-Ring Highway). Data from the Shanghai Statistics Bureau shows that till the year 2003 a total of 5090 high-rise apartment buildings was found in the inner-city area, which adds up to a total floor area of 85.61 million square meters and accounts for nearly 44% of the overall residential building floor area in the inner city.

High-rise building is believed by some as an ecological progressive and environmental sustainable development type by virtue of the intensive use of small plots of land, e.g. [2]. Compared with the low-rise high-density model, high-rise housing in Shanghai is also thought to have positive impacts on heat island mitigation by releasing land at ground level for green space and wind corridors [3]. However the existing thermal conditions of the typical high-rise housing quarters in Shanghai remain largely unexplored. The relevant study becomes imperative as the degrading tendency of urban thermal environment of Shanghai shows no sign of retreat.

Urban heat island (UHI), as an indication of urbanization impact on the urban thermal environment, has gradually increased in Shanghai [4], and the extent of the UHI-affected area has developed largely in accordance with the urban sprawl process [3]. Summertime UHI gives rise to a number of problems. It increases housing cooling loads and electricity consumption [5,6]. It exacerbates thermal discomfort [7]. It also has detrimental effects on human health especially for the senior citizens, and worsens the scenario when extreme heat waves attacks Shanghai, for instance, the intensive heat wave occurred in Shanghai in 1998 which caused a large number of deaths [8]. It would be significant to study UHI in high-rise housing quarters in Shanghai because they belong to the most material and inhabitant -intensive development type, in other

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words, the symbol of the highest level of urbanization. Based on the recognition that UHI is in part due to choices in materials, vegetation and urban design [9], the present study adopts an empirical approach to investigate the impacts of greenery and urban design parameters on UHI intensity in selected high-rise residential quarters in the inner-city of Shanghai.

2. Research related to density, layout and greenery

Building density and plot layout are directly associated with urban canyon geometry and orientation, which have significant impacts on UHI intensity [10]. On the other hand, urban built form is the most interesting topic to architects and urban designers and the study results could be readily apprehended and referenced in their practice. Studies on linking urban form factors with the climatic impact thus necessitate joint efforts from architecture, engineering, meteorology and other disciplines. For instance, sensible heat flux (Q_H) intensity, as an important factor in determining air temperature distribution, was numerically studied on a Japan large housing development [11], the data shows that, under the same plot density (floor area ratio), the square (enclosed) plot is the most intensive type in terms of Q_H, followed by the linear plot and the interspersed plot; but at night Q_H from the linear plot site becomes larger than the enclosed plot site. The day–night difference necessitates separating the two periods in study. In another study, the urban forms of a courtyard (enclosed), a pavilion and a variation of pavilion were parametrically analyzed and compared based on average daylight availability, shading density and sky view factor. The results, with the justification by observation on vernacular architecture, favor the conclusion that in a hot-arid climate, the courtyard (enclosed) form is the best [12]. Based on a hot–humid climate, an experimental Study by Shashua-Bar et al. focuses on the cooling effect of vegetation and urban geometry in a low-rise and high-density environment. It is found that, on average about 80% of the cooling effect is contributed by tree shading [13]. In terms of canyon orientation, a study shows that the east-western oriented canyon appear to be the most thermally stressful compared with other orientations. Increasing flanked building height and implementing shading devices such as trees or galleries are proposed as critical measures in ameliorating thermal discomfort in this configuration [14].

Loss in vegetative cover in urban area is an important factor which causes UHI [10,15,16]. Therefore, urban reforestation is advocated as an efficient UHI countermeasure [17,18]. But an urban high-rise environment exerts influence upon urban greenery in many respects. The real environmental cooling performance could thus be affected. On one hand, the radiation and mass exchange of greenery with its environment is changed by differed thermal properties of built surroundings compared with its rural counterparts [19]. On the other hand, the heat dissipation (self-cooling) process of greenery, which depends on water availability, wind pattern and leaf surface temperature, is altered in highly urbanized areas: the relatively thin growing substrates generally provides insufficient water unless regularly irrigated; and air movement can be stagnated where surrounding tall buildings act as wind shelters to hinder latent heat fluxes transfer. Further, other urban factors such as air pollutants and overheated air could cause leaf stomata to be blocked or automatically shut off, which affect the vegetation evaporative cooling [20,21]. Shading by vegetation canopies faces challenge in high-rise building environments as well, when considered on a diurnal basis. The question is: do we still need tree shade when tall buildings already provide shading? Probably yes if the peak noon in summer days are within consideration, when the sun is right above head and buildings hardly provide any protection. The answer is also positive if there is a large amount of diffused radiation from sky and reflected solar radiation from building surfaces. However, a dense tree canopy in deep urban canyons reduces the viewable sky and undermines long-wave irradiative cooling at night, thus aggravate thermal discomfort. Therefore a dilemma of implementing trees seems exist in a high-rise setting. Considering the complicated interaction between greenery and its high-rise environment, an empirical study would help reveal the relationship of real thermal conditions with the physical (design) parameters, which is valuable for future parametric studies, setting the Shanghai urban and climate as the background.

Fig. 1. Locations of three sites in the inner-city of Shanghai.

3. Field work procedure and selection of variables

3.1. The three sites under study

The three sites chosen for field work are Haiyue Garden (coded as Site A); Xiling New Town (Site B) and Yishan Estate (Site C). Ideally for studies in this nature, all the sites should be located at the places with identical surroundings, i.e., the same characteristics in surrounding topography, land use, and building/population density so that the background effect on the on-site thermal condition can be minimized. However, in practice it turns out to be very difficult, if not impossible, to find such perfect samples. Nevertheless, efforts had been made in the site screening process to ensure that the three sites are located in urban districts with the same land use (residential) and similar building density. The three sites are all located at the south-west part of the inner city (Fig. 1), and are surrounded by roads at two sides and other residential quarters at the other sides. Furthermore, there is no sizable green space or water body in the nearby influential area for any of the

Table 1
Land use and built properties of Sites A, B and C.

Site name	A	B	C
Plot type	Semi-enclosed	Interspersed	Long-linear
Plot area (ha)	3.19	4.40	3.98
Total floor area (X104m2)	14.46	27.92	8.52
Floor area ratio (FAR)	4.54	6.35	2.14
Green ratio (%)	40	20	61