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Urban design to lower summertime outdoor temperatures: An empirical study on high-rise housing in Shanghai

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ABSTRACT

This research investigates the effect of urban design factors on summertime urban heat island (UHI) intensity. Ten high-rise residential quarters in the inner city of Shanghai were empirically investigated during mid July to mid August in 2008. On-site design variables were developed to quantify the thermal impacts from density, building layout and greenery. The design variables that were measured on site were correlated with the variation in UHI intensity during the day and night. The results show that variations in UHI are in part due to site planning, building design, and greenery. The overall daytime and nighttime UHI models explain up to 77 and 90 percent of UHI variation, respectively. On-site shading from either buildings or vegetation canopy is the most important factor influencing daytime UHI. The shading factor can distort and dilute behavior of other variables, e.g., green ratio and surface albedo. Nighttime UHI is more complicated due to the influence from anthropogenic heat, and is significantly related to greenery density and coverage. Based on the findings, potential design strategies are proposed in an effort to mitigate UHI, including manipulating building layout and mass to improve shading during the day while facilitating site ventilation at night and increasing site vegetation cover through strategic tree planting. Further recommendations for urban planning approaches to mitigate UHI on the urban scale are proposed.

1. Introduction

While half of the world's population had become urban dwellers by 2006, predictions suggest that the number of Chinese citizens living in urban areas will reach 50% by 2020 [1]. The ongoing urbanization in China has been posing a huge pressure on the urban thermal environment. A well-studied phenomenon is the urban heat island (UHI) effect, which is the temperature difference between urban and its surrounding undeveloped areas [2]. The UHI in Shanghai has been studied since the 1950s [3]. The UHI effect is a historical reality in Shanghai and the intensity has been enhanced with time [4].

UHI is a multi-scale phenomenon [5]. Scale is a very important consideration in urban climatology, in that "failure to recognize the role of scale in urban climatology can lead to serious errors in the experiment design, model development and interpretation of results" [6]. An important concept to help understand scales is the distinction between urban canopy layer (UCL) and urban boundary layer (UBL) [2]. The UCL refers to the air volume beneath the building roof level, and is mostly influenced by micro-scale processes in urban canyons. Right above the UCL is the UBL which is influenced by the general urban surface and is a meso-scale phenomenon [2]. Compared to the relatively more homogeneous UBL, the climatic conditions within the UCL can vary significantly from one location to another, as it is largely determined by the physical properties of the immediate surrounding conditions [7]. As shown in the model given by Oke (Eq. (1) [2]), the heat gain in the UCL (Q^*, net all-wave radiation of the volume exterior from the sun and Q_F, anthropogenic heat, including human metabolic heat release and fuel combustion heat release) is equivalent to heat fluxes dissipated (including Q_H, sensible heat flux and Q_E, latent heat flux), stored (ΔQ_S) and advected (ΔQ_A).

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \quad (1)$$

Urban canyon geometry significantly changes the energy flow and thermal balance within the UCL air volume [8,9]. The geometrical and materialistic features of urban canyons exert heavy impacts on buildings/ground surface temperature, air temperature and canyon winds, and thus the overall thermal conditions and comfort levels [10]. The UCL heat island effect can be regarded as an epitomization of those complex influences. The

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Table 1
Hypothesized urbanization effects on the UCL heat islands (after Ref. [2]).

Features of urbanization	The underlying energy balance changes caused by the features	Altered energy balance terms leading to positive thermal anomaly
Building volume and layout	Increased surface area and multiple reflection Reduction of sky view factor Affect direct solar heat gain particularly under clear skies Reduction of wind speed	Increased absorption of short-wave radiation Decreased long-wave radiation loss Absorption of direct short-wave radiation Decreased total turbulent heat transport
Construction materials	Increased thermal admittance	Increased sensible heat storage
Loss of vegetative cover	Increased "water proofing" Decreased tree canopy shading	Decreased evapotranspiration Increased radiation heating at day; Increase irradiative cooling at night
Building/traffic heat	Increased anthropogenic heat	Anthropogenic heat source
Air-pollution	Greater absorption/re-emission	Increased sky long-wave radiation

UCL heat islands have been attributed to changes in urban geometry, building and pavement materials, anthropogenic heat emission and to a less extent air pollution [2,11,12]. What Oke proposed as the contributing factors more than twenty years ago (Table 1) has been supported by numerous published studies ever since, as been summarized in Ref. [7,12]. Therefore, to understand the influence of urban design factors on the UCL climate, the measured climatic parameters should be examined in relation to the urban physical features immediately around the measurement points.

The potential of appropriate urban design strategies to moderate the UCL thermal environment has been studied in terms of manipulating building density [13,14], building layout/street orientation[15,16] and greenery [17,18]. In a planning and design point of view, it is therefore possible to identify and apply proper climate-sensitive design strategies in areas under rapid urbanization or urban renewal, to accommodate ever-increasing population without compromising outdoor comfort, air quality and building cooling energy efficiency [19–21].

Knowledge derived from urban climate studies has been embodied in a number of green building rating tools developed in various countries, to recognize UHI mitigation efforts and advise on appropriate strategies. For instance, the Leadership in Energy and Environmental Design (LEED) from the US offers credits for efforts made to reduce UHI by providing on-site shading, pervious pavement, and solar-reflective roof/ground materials [22]. The Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) from Japan develops a specific sub-tool, i.e., CASBEE-Heat Island relaxation (CASBEE-HI), to systematically evaluate a project's UHI relaxation measures with regard to five aspects, i.e., site ventilation, shading, ground surface cover, building cladding materials, and anthropogenic heat [23]. In the Evaluation Standard for Green Buildings in China, one credit is awarded to residential developments that control the on-site daily mean UHI intensity within 1.5 °C [24]. But, the current version of the Standard does not give any recommendation as how to achieve this reduction and therefore is difficult to instruct planning and building design practices at early stages. In this regard, an empirical understanding on the thermal impacts of UHI mitigation measures in the local context would help to set an appropriate benchmark. On the other hand, an empirical study based on field measurement is of particular value compared to the numerical approach, in that the results can be more easily related to real problems [25].

This empirical study aims to establish statistical relationships between measured outdoor thermal anomalies (in terms of UHI intensity) and urban design parameters in selected high-rise high-density housing quarters in the inner city of Shanghai, China. Our hypothesis is that, with the meso-scale UHI "background" effect being carefully controlled, a significant part of outdoor thermal anomalies can be explained by critical on-site urban design factors.[1]

2. Methodology

As Mirzaei and Haghighat has pointed out, the field measurement approach to UHI study has several limitations: expensive and time-consuming; incapable of achieving an overall picture of UHI pattern; and difficulties in reaching consistent results even with sufficient data collected, because of the numerous contributing factors [5]. Indeed, this study focuses on the micro-climatic effects of urban design parameters, but for a field study, the on-site measured climatic data are the synthetic results of the *regional*-scale, *meso*-scale and *local- to micro*-scale climates. Furthermore, the UHI pattern is dynamic with seasonal change in background climate (i.e., radiation, temperatures, wind patterns, etc.) [3,26] and spatial variation in geographic location (i.e., urban central to suburb to rural) [27]. Therefore, it is impossible to measure the "site-specific" climatic effect unless those background (seasonal, geographical and urbanization) effects can be effectively controlled. The study therefore used the following precautions:

- Geographically, all the sites are located within the inner city of Shanghai.
- Topographically, effect of altitude is assumed marginal, as Shanghai is a flat city situated on a fluvial plain; sites were carefully selected and grouped so that each group of sites falls within a specific Urban Climate Zone (UCZ) (Section 2.1), and the sites within each UCZ are bounded with similar landscape elements (i.e., water bodies, urban parks, highways, etc.). Each group of sites was measured simultaneously;
- Seasonally, the period of field measurement is classified into two weather periods based on meteorological data of cloud cover and air temperature (Section 2.3).
- Data are firstly analyzed on a UCZ basis, and then with the introduction of a set of variables describing the background effect, four UCZs are aggregated for overall analysis.

2.1. Site selection

2.1.1. Urban climate zoning

Urban climate mapping (UCMap) has been carried out since the 1970s in Germany, to evaluate the effect of urbanization on urban

[1] A preliminary analysis on the UCZ 1 out of the overall four UCZs has previously been presented in: Yang F, Lau SSY, Qian F. Summertime heat island intensities in three high-rise housing quarters in inner-city Shanghai China: building layout, density and greenery. Building and Environment 2010; 45 (1): 115–134.