



Intra-urban differences of mean radiant temperature in different urban settings in Shanghai and implications for heat stress under heat waves: A GIS-based approach

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ARTICLE INFO

Article history:

Received 1 August 2016

Received in revised form 4 September 2016

Accepted 6 September 2016

Available online 9 September 2016

Keywords:

Mean radiant temperature

SOLWEIG

Heat stress

Shanghai

ABSTRACT

The mean radiant temperature (T_{mrt}) is an effective indicator to characterize the urban thermal radiant environment and assess outdoor thermal comfort and heat stress. In this study, the SOLWEIG model (Solar and Long Wave Environmental Irradiance Geometry) was employed to investigate the spatial variation of T_{mrt} in different urban settings in Shanghai. The model was tested against six directional radiant flux density measurements and showed good performance in Shanghai's urban environment. Two different urban settings with different building geometry and vegetation cover were used as case study sites. A typical heat wave day in 2013 was selected to investigate the daytime radiant heat stress intensity. Spatial analysis modules were developed and the Radiant Heat Stress Intensity index was defined. The study reveals that in Shanghai under heat waves the heat stress induced by the thermal radiant environment is quite severe, with T_{mrt} commonly well above 60 °C in daytime, and intra-urban T_{mrt} differences are largely influenced by building density and height, street orientation and vegetation. Open paved spaces and space near sunlit walls are the places that have the highest T_{mrt} . The study shows that the spatial variation of T_{mrt} can be used to identify thermally vulnerable areas and hotspots in complex urban environment, and provide implications for urban design towards the mitigation of heat stress in high-density cities.

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1. Introduction

Heat stress in cities is becoming increasingly severe due to the unprecedented urbanization and global warming paces. Urban overheating not only has large impacts on the energy consumption in buildings [1–3], but also significantly affects outdoor thermal comfort and therefore citizen's behavior and lifestyle [4]. With respect to people's comfort, health and well-being, daytime heat stress will cause health risks such as fatigue, morbidity, or even mortality in extreme weather conditions such as heat waves [5–7].

Besides the high air temperature in city centers which has been commonly observed and widely studied [8,9], the thermal radiant aspect of the urban environment has drawn much attention only

in recent years with the progress in remote sensing technologies and in-situ monitoring techniques. In fact, convective fluxes of sensible heat and latent heat are more significant in directing human energy balance and thermoregulation as compared to conductive heat, especially in strong solar exposure conditions. Therefore the thermal radiant environment plays a more important role in affecting outdoor thermal comfort in hot summer. There have been an increasing number of research studies aiming at mitigating urban heat island and reducing heat stress in cities from the thermal radiant perspective [10–12]. Comprehensive reviews have also been conducted on the state-of-the-art technologies to mitigate UHI, especially from the thermal comfort aspect, such as the development of reflective materials, cool roof and pavement, and urban greening [13,14].

The mean radiant temperature (T_{mrt}) is the most important meteorological parameter that characterizes the effect of thermal radiant environment on human thermal comfort [15]. It is defined

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as “the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure” [16]. By definition, T_{mrt} parameterizes the holistic effect of the complex radiation fluxes of the thermal radiant environment into a single temperature-dimension index ($^{\circ}\text{C}$). In a complex urban environment, the radiation fluxes vary considerably in outdoor spaces because of the shading generated by buildings and vegetation, and also because of different surface materials. Therefore T_{mrt} can exhibit significant spatial variation even within a short distance. For example, Mayer and Höppe [17] showed through in-situ meteorological measurement that the T_{mrt} difference between a sunlit street canyon and a nearby shaded street canyon can be up to 30°C in the early afternoon, whereas the difference of the air temperature (T_a) is less than 3°C . This suggests that T_{mrt} can be a more suitable index for characterizing the intra-urban differences of thermal comfort conditions as compared to traditional meteorological indices such as T_a , especially in complex urban environment. Therefore T_{mrt} has been widely adopted across the world in urban human-biometeorological studies to parameterize the level of thermal comfort and heat stress in hot summer [18–23]. Thorsson et al. [24] also found that T_{mrt} can effectively predict the risk of mortality of senior citizens induced by heat stress.

In urban outdoor spaces, T_{mrt} is primarily determined by building geometry, street layout, albedo of facade and ground, and vegetation cover. These components can be effectively altered by design interventions. Therefore understanding how the spatial variation of T_{mrt} is affected by different urban settings is important and can provide valuable implications for climate-responsive urban design and planning. An increasing number of studies have hence addressed this concern across different scales, including micro scale such as street canyons [25–27] and urban open spaces [28], neighborhood scale such as residential communities [29], and district scale with various building shapes and street orientations [30–34]. It is commonly found that building geometry and vegetation plays the most significant role in affecting T_{mrt} and thus the overall thermal comfort [25,27,35,36], in contrast the contribution of surface albedo is rather minor [37,38]. So far most of the studies were carried out in urban environment with low or moderate density, such as mid-size European cities [27,33,36]. In the high-density urban environment of a metropolitan such as Shanghai, the spatial variation of T_{mrt} is further complexed by the combination of deep street canyons, shadow casted by high-rise buildings, near-wall sunlit spaces, etc. Lau et al. [39] took the downtown center of Hong Kong as an example and addressed the issue in high-density urban environment. On the other hand the discussion was qualitative rather than analytical. No quantitative comparisons were given for the spatial variation of T_{mrt} of the selected “open area” and “denser area” which are separated by a road, and no vegetation was included in the estimation of T_{mrt} even though there were urban parks and green spaces, which are also essential urban elements. Furthermore the use of summer average weather data may be less revealing since Thorsson et al. [24] have shown that daily maximum T_{mrt} can better reflect the level of heat stress as indicated by mortality.

The objective of the present study is to investigate the spatial variation of T_{mrt} as affected by different urban geometry and vegetation in high-density cities and its implication for heat stress during heat waves. Two different urban settings in Shanghai's downtown area were selected as the study sites. The Solar and Long Wave Environmental Irradiance Geometry (SOLWEIG) model [35,40] was validated with field measurement and used to simulate T_{mrt} pattern for a real summer hot day to examine the actual meteorological conditions. The index of *Radiant Heat Stress Intensity* (RHSI) was defined to evaluate heat stress intensity from the thermal radiant aspect. Spatial analysis of the spatial variations of T_{mrt} was conducted, based on which heat stress areas were identified

and urban design implications for mitigating urban heat stress were proposed.

2. Methods

2.1. Study area

Shanghai ($30^{\circ}40'\text{N} \sim 31^{\circ}53'\text{N}$, $120^{\circ}51'\text{E} \sim 122^{\circ}12'\text{E}$), the biggest city in China, is located on the alluvial terrace of the Yangtze River delta with average elevation of 4 m above sea level. It has a northern subtropical monsoon climate, with a mean annual T_a of 17.2°C , and monthly maximum and minimum mean T_a of 30.2°C in July and 1.9°C in January for the last 30 years, respectively. The city's administrative boundaries cover a total terrestrial area of 6340.5 km^2 excluding estuary waters. The city has a total population of 24.15 million, including both permanent and non-permanent residents. As one of the most rapidly urbanizing cities in China, Shanghai is also suffering increasingly severe heat stress. In 2013, the city experienced its hottest summer in the last 140 years since weather data was recorded. Eight consecutive days of T_a above 38°C and 25 days of T_a above 35°C were recorded in July. The highest official T_a of 40.6°C was also recorded by the city's benchmark observatory. During the hot spell, hospital admissions generally increased by 30%, and at least 10 people died from heat stroke [41,42]. In such cases, identifying urban hot spots and areas vulnerable to heat stress is particularly important for implementing alerting and protection measures.

The Lujiazui (LJZ) central business district is located in the Pudong New District on the eastern bank of the Huangpu River just across the Bund. The area has a mixture of commercial, business and high-end residential land uses. There are a total number of 45 super high-rise buildings taller than 200 m in LJZ, and the tallest building, Shanghai Center, is 632 m high. The area is also characterized by abundant urban open spaces and greenery including parks and roadside trees. In comparison, the old residential neighborhood of Xiaonanmen (XNM) is located in the Huangpu District on the western bank of the Huangpu River. The area is densely packed with old residential buildings normally 1–4 story high. Although there are a few tall buildings built more recently, none of them is taller than 120 m. Because of the limited space, vegetation such as trees and shrubs is extremely scarce in XNM, and in some narrow streets there is literally no urban greenery. The area is also dominated by the regular E-W and N-S street orientations. These two areas represent two different urban settings of the high-dense city center of Shanghai. Fig. 1 shows the locations of LJZ and XNM in Shanghai and snapshots of their typical street scenarios. Two 1 km by 1 km sites were selected from LJZ and XNM as case study sites. Fig. 2 shows the digital elevation model (DEM). Table 1 summarizes the morphological information of the two sites.

2.2. SOLWEIG model: validation and simulation

The SOLWEIG model (Solar and Long Wave Environmental Irradiance Geometry) [35,40] is a computational model that can simulate the spatial variation of T_{mrt} in a complex urban environment. SOLWEIG calculates T_{mrt} by simulating the 3-D radiant flux densities of the surrounding environment, which is based on the integral 3-D radiant environment monitoring technique proposed by Höppe [19]. The monitoring method has been considered as the most accurate way to determine T_{mrt} values in outdoor environment [43]. SOLWEIG rebuilds the measurement procedures in a virtual sense, i.e. simulating the shortwave and longwave radiant flux densities from the six directions of the surrounding environment (east, west, north, south, upward and downward) and estimating angular factors (proportion of radiation received by the

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