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Numerical modeling of outdoor thermal comfort in 3D

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ABSTRACT

With the rise in urban air temperature, heat stress and thermal discomfort are challenging the livability of urban environments. To respond to this concern, we employ numerical modeling to evaluate the spatial and temporal variabilities of thermal comfort and introduce a simulation tool: outdoor thermal comfort in 3D (OTC3D). The model builds upon the work by Nazarian et al., 2017, and is a) extended to evaluate realistic urban configurations, b) validated against measurements, c) enabled to intake a wide resolution range of microclimate parameters (modular approach), and d) made available on an open-source platform. Using OTC3D, we evaluated outdoor thermal comfort (OTC) in two urban configurations: idealized and realistic. In the realistic configuration, we demonstrate the functionality of the model in presenting the variability of OTC in an urban neighborhood. Using the idealized configuration, on the other hand, we performed sensitivity studies regarding the effects of urban density and realistic surface heating. First, we observed that thermal comfort changes non-monotonically with urban density, as the ensuing change in wind speed and radiation patterns have counteracting effects on thermal comfort. Accordingly, to achieve the desired thermal comfort in hot climates, strategies to enhance urban ventilation are favored in higher densities, while strategies to minimize radiation are needed for lower urban packing densities. Furthermore, we observed that realistic distribution of surface temperature is critical when urban density is high (e.g. $\lambda_p = 0.44$). Therefore, approximations of surface temperature found in existing thermal comfort models are not suited for high-density urban areas. This further motivates the modular approach to improve the accuracy of thermal comfort analysis.

1. Introduction

The rapid rise in urbanization alongside global climate change is posing a threat to the sustainability and livability of our future cities and the well-being of their citizens (Watts et al., 2015). Among the prominent challenges, climate and environmental concerns such as urban heat and air quality are gaining worldwide attention (Intergovernmental Panel on Climate Change, 2014), and particularly, heat stress during extreme weather events is of growing concern as mortality is strongly associated with temperature metrics during heatwaves (Baccini et al., 2008; Kovats and Hajat, 2008; Tapper et al., 2014; Xu et al., 2016). In summer 2015 alone, over 11,000 people were hospitalized due to hot weather in Japan, with greater concentrations in such urbanized regions as the Greater Tokyo Area (Takane et al., 2015), while a heatwave in southern India led to over 1500 deaths (Zhou & Shao, 2017). These

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Nomenclature

Abbreviations

LOD	Level of Detail (Biljecki et al., 2016)
OTC	Outdoor Thermal Comfort
OTC3D	Outdoor Thermal Comfort in 3D model
RH	Relative Humidity
SET	Standard Effective Temperature (°C)
SVF	Sky View Factor
WVF	Wall View Factor

Greek symbols

α_K	Shortwave absorption coefficient of a person
α_L	Longwave absorption coefficient of a person
β	Solar altitude angle (degree)
γ	Solar azimuth angle (degree)
λ_P	Plan area density
σ	Stefan-Boltzmann constant(5.67×10^{-8} Wm^{-2} K^{-4})
ε_{sky}	Emissivity of the sky
ε_{surf}	Emissivity of urban surfaces

Roman symbols

H	Building height (m)
W	Canyon width (m)
$F_{sky\to p}$	View factor between the visible sky and a person
$F_{sol\to p}$	View factor between the shortwave sources and a person
$F_{surf\to p}$	View factor between urban surfaces and a person
h_{se}	Standard evaporative heat transfer coefficient ($\text{W m}^{-2}\,\text{Pa}^{-1}$)
H_{sk}	Heat loss from the skin (W m^{-2})
h_s	Standard heat transfer coefficient ($\text{W m}^{-2}\,\text{K}^{-1}$)
K_{dif}	Diffuse shortwave radiation flux density (W m^{-2})
K_{dir}	Direct shortwave radiation flux density (W m^{-2})
L_{atm}	Longwave radiation flux density from the atmosphere (W m^{-2})
L_{surf}	Longwave radiation flux density from urban surfaces (W m^{-2})
N_{dir}	Total number of discretization directions for SVF calculation (set by user)
N_{vis}	Number of visible surface grids (calculated for each pedestrian position)
P_{SET}	Saturated water vapor pressure at standard effective temperature (kPa)
P_{ssk}	Saturated water vapor pressure at skin temperature (kPa)
P_{so}	Vapor pressure at T_{so} (hPa)
T_a	Air temperature (°C)
T_{mrt}	Mean radiant temperature (°C)
T_{sk}	Skin temperature (°C)
T_{so}	Standard operative temperature (°C)
T_{surf}	Urban surface temperature (°C)
v	Wind speed (ms^{-1})
w	Skin wetness

concerns are particularly pertinent in tropical cities, where high temperature combined with high humidity limit the body's ability to release heat through evaporative cooling (Ahmed, 2003).

As the first step for combatting extreme thermal stress in urban areas, addressing "thermal comfort," i.e. human sensation of the thermal environment, in indoor and outdoor urban spaces is crucial in the context of city livability. To do so, efforts are made to improve the thermal comfort of enclosed indoor spaces by enhancing the natural ventilation (Khan et al., 2008; Prajongsan and Sharples, 2012), minimizing the transmitted solar radiation by altering the design and window properties (Chow et al., 2010), or with the use of ventilation systems such as fans and air conditioning. For outdoor spaces, however, the lack of thermal boundary and the exposure to the direct radiation call for alternative strategies to maintain the desired thermal comfort level. One of the main strategies to achieve this goal is by improving the design workflow to account for outdoor thermal comfort (OTC).

Addressing OTC through design strategies requires a deep understanding of the topic, covering a range of physical and social considerations. Models and techniques for thermal comfort analysis should address the needs of urban planners and designers, while maintaining a holistic and accurate representation of (micro-)climatological parameters. Such objectives call for more advanced and in-depth analyses of OTC, which motivate the present study. Here, after reviewing the state-of-the-art knowledge (Sec. 1.1), we introduce a methodology that moves towards a comprehensive thermal comfort analysis by employing a modular approach, and use this methodology to answer research questions detailed in Sec. 1.2.

1.1. Research background

Obtaining an accurate prediction and measurement of outdoor thermal comfort is complex as thermal comfort depends on the combined effects of various microclimate parameters (such as air temperature, humidity, radiant exposure, and wind speed) as well as the individual's experience of the thermal environment based on his/her physiology, psychological state, and expectations (Höppe, 2002). Accordingly, thermal comfort is described by a range of thermal comfort indices and models (Coccolo et al., 2016) that integrate such contributing factors.

The development of thermal comfort indices and models dates back to the late 1930s when Gagge (1936) introduced the first simplified "two-node model" for describing the energy exchange between the human body and the environment. Subsequently, various indices were developed to quantify human comfort and thermal stress in both indoor and outdoor spaces. Indices of thermal comfort in indoor spaces are more easily established due to the relative stability of the indoor environment (in terms of air temperature, humidity, radiation, and air flow) and the ability to control it mechanically (Coccolo et al., 2016). On the contrary, the spatial variability in solar exposure and wind speed in outdoor spaces, as well as the temporal variability of microclimate parameters,