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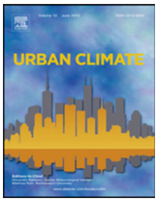

Predicting outdoor thermal comfort in urban environments: A 3D numerical model for standard effective temperature

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ABSTRACT

With the rapid rate of urbanization, outdoor thermal comfort is a growing health concern in densely-built areas. Accordingly, in order to achieve a comprehensive solution to urban environmental problems, more detailed and accurate prediction of outdoor thermal comfort is needed alongside building energy and urban wind flow analyses. To address this need, this study introduces an improved methodology of predicting outdoor thermal comfort and its spatial variability in urban streets using the comprehensive index standard effective temperature (SET). The improvement of the thermal comfort calculation is twofold. First, CFD simulations of the flow field dynamically coupled with the realistic urban surface heating are used to provide the input variables for the SET calculation. The CFD results provide detailed information on the heterogeneous urban flow field as a critical determinant of human comfort. Second, the SET calculations are improved by introducing a detailed model of mean radiant temperature that incorporates a) the visibility of urban surfaces to the pedestrians at any point, b) the spatial distribution of sky view factor, and c) inter-building shadowing and shortwave radiation effects on thermal comfort. These improvements allow for evaluating the spatial distribution of SET. Additionally, several sensitivity studies are carried out for an idealized configuration representing a compact low rise urban zone. The SET evaluated at the pedestrian level shows that urban density, wind patterns, and solar position concurrently influence thermal comfort. A sensitivity study on the effect of urban density reveals that higher urban concentration can favourably impact thermal comfort in warm climates due to the increased shading, despite the associated increase in air temperature and building energy consumption. The current study also demonstrates the critical importance of a comprehensive thermal comfort model that considers the flow field patterns as well as the realistic heating distribution of urban surfaces. We find that even in the shaded areas in the street canyon, SET changes up to 10 °C due to the wind sheltering in the urban roughness. Following this methodology, more complex scenarios can be evaluated in order to evaluate the effect of urban design on thermal comfort, and ultimately achieve a climate-conscious design.

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Nomenclature

SET	Standard effective temperature (°C)
SVF	Sky view factor
UHI	Urban heat island
WVF	Wall view factor
β	Altitude angle
γ	Azimuth angle
σ	Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4})
ε_{sky}	Emissivity of the sky
ε_{urb}	Emissivity of urban surfaces
a_p	Shortwave absorption coefficient of a person
E_{sky}	Long-wave radiation intensity from the atmosphere (W m^{-2})
E_{sol}	Solar radiation intensity (W m^{-2})
E_{urb}	Long-wave radiation intensity of urban surfaces (W m^{-2})
F_{sky-p}	View factor between the visible sky and a person
F_{sol-p}	View factor between the short-wave sources and a person
F_{urb-p}	View factor between urban surfaces and a person
h_{es}	Standard evaporative heat transfer coefficient (W m^{-2} Pa^{-1})
H_{sk}	Heat loss from the skin (W m^{-2})
h_{sp}	Standard heat transfer coefficient (W m^{-2} K^{-1})
p_{SET}	Saturated water vapor pressure at standard effective temperature (kPa)
p_{ssk}	Water vapor pressure at skin temperature (kPa)
T_a	Average air temperature (°C)
T_b	Average body temperature (°C)
T_g	Ground temperature (°C)
T_{mrt}	Mean radiant temperature (°C)
T_{so}	Standard operative temperature (°C
v	Wind velocity (m s^{-1})
w	Skin wetness

1. Introduction

By 2050, two-thirds of the world population is expected to live in cities (United Nations, 2014). While urbanization provides solutions for resource efficiency and economic growth, it also imposes a variety of environmental challenges. One major environmental consequence of urbanization is the urban heat island (UHI), i.e. the rise of temperature in densely built areas relative to the rural environment (Kim, 1992; Oke, 1973, 1981; Bornstein, 1968), which is responsible for significant economic and health concerns due to increased heat stress in densely built areas (Tan et al., 2010; Lo and Quattrochi, 2003; Mavrogianni et al., 2011). Consequently, the thermal sensation and experience of urban dwellers, i.e. thermal comfort, is shaped as a response to the UHI formation.

Thermal comfort has been evaluated by means of measurements, surveys, and numerical methods; and thermal comfort indices that incorporate numerous microclimate factors have been introduced. Field studies (Nikolopoulou et al., 2001; Lin, 2009; Chow et al., 2016) combined microclimate measurements and surveys from pedestrians in order to evaluate thermal comfort through both objective (microclimate) and subjective (physiological, psychological and behavioral) parameters. Such field studies have verified the role of urban design on the thermal sensation of urban dwellers, and are invaluable for understanding the complex nature of human comfort in urban areas. However, field measurements fall short in 1) identifying and isolating the variables that markedly affect urban microclimates; and 2) representing the detailed spatial variability of thermal comfort indices.

Numerical methods can further address these shortcomings. However, computing thermal comfort is complex in its nature, not only due to its subjectivity, but also due to the consideration of various meteorological parameters involved (such as air temperature, wind speed, humidity, and radiant temperature). Accordingly, methods of describing thermal comfort, i.e. thermal comfort indices, vary in their assumptions and the underlying thermal models (Gagge, 1971; Azer and Hsu, 1977; Epstein and Moran, 2006; Honjo, 2009). For instance, the predicted mean vote (PMV) was developed based on the Fanger comfort model (Fanger, 1967, 1970) as an empirically-based index, and is more applicable for field measurements of thermal