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Urban development and pedestrian thermal comfort in Melbourne

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ABSTRACT

In October 2013, "Plan Melbourne" was released by the Victorian government to outline the vision for Melbourne's growth to the year 2050. The City of Melbourne's draft municipal strategic statement identified "City North" as a great urban renewal area that can accommodate a significant part of the growth. Structure plans provide guidance to the community, planners, business, government and developers about the appropriate directions and opportunities for future changes in City North. Proposing street hierarchy, increasing the building heights, expanding the urban forest by increasing tree canopy coverage, implementing green roofs and overall transition from a low-rise to medium rise urban area are some of the strategies presented in structural plans. This study investigates the effect of future structural plans presented in "Plan Melbourne" on pedestrian thermal comfort in City North for extreme hot summer days. A three-dimensional microclimatic modelling tool ENVI-met 3.1 was used to evaluate the outdoor human thermal environment for the existing and future scenarios proposed by the Victorian government. Field measurements were carried out to validate ENVI-met and examine its ability in addressing the research objectives. Structural plans were modelled t in three stages; increased building height, adding tree canopy coverage and adding green roofs. The study showed that deeper canyons, higher aspect ratios and lower sky view factors in future scenario contribute to lower level of mean radiant temperatures (42 °C–64 °C), compared to the existing scenario (49 °C–60 °C). Physiological equivalent temperature (PET) was improved by 1 °C–4 °C as a result of "Increased building height" scenario. Increasing the tree canopy coverage caused 1 °C–2 °C reduction on PET level and adding a green roof did not show any improvement on PET at pedestrian level. Although the study showed a slight improvement in PET after implementing future structural plans, it was necessary to further improve PET level, particularly during certain hours of the day. Therefore long term planning strategies (integrating public realms with small urban parks and increasing the tree canopy coverage from 40% to 50%) were proposed and modelled to examine their effectiveness in further improving thermal comfort in an extremely hot summer day. Implementing future structural plans and proposed scenarios together resulted in 5.1 °C improvement in the PET in an extremely hot summer day. The study also indicated that aspect ratio (H/W) is the most efficient strategy in decreasing Tmrt and PET during the day. Integrating climatic knowledge into planning practices in Melbourne metropolitan area would lead to less vulnerability to the extreme heat events and reduce the adverse impacts of increased air temperature on public health.

1. Introduction

The combination of large populations, densely built structures and sealed surfaces in cities do not represent ideal conditions for tackling a changing climate. A climate in which weather events become more extreme may lead to an increase in flooding, droughts and heat stress, causing not only financial damage but also threats to public health and safety (Gao et al., 2015; Field et al., 2014). Therefore, integration of urban climatic knowledge into planning policies and the development of mitigation technologies against climate change have received further attention in the last few decades.

The Bureau of Meteorology and CSIRO climate change modelling predict that Melbourne will experience more extremely hot days. The city currently experiences an average of nine extremely hot days of over 35 °C every year, and this number is expected to increase to 11 days by 2030 and to 20 days by 2070.

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On the other hand, Melbourne has witnessed a remarkable population growth over the past few years. ABS projections predict that Melbourne population will reach 6 million in 2056 (Chen and Ng, 2013). To accommodate this ongoing population growth, an additional 600,000 new dwellings must be constructed, among which 316,000 dwellings must be built close to the central business district (CBD) (Algeciras et al., 2016). To outline the vision for future growth, "Plan Melbourne" was released in October 2013. The plan presents the planning strategies that must be adopted through short, medium, and long-term period of time.

One of the main components of "Plan Melbourne" is to expand Melbourne's CBD to cover its northern area which is known as City North. The plan aims to develop City North into a compact, dense, medium-rise urban neighbourhood which can accommodate 22,000 residents by 2040. State government established structural plans to provide a framework for future development in this area. Structural plans determine the future of built form, morphology and urban forest strategies in this area.

Given the increasing number of hot days per decade in Australia and particularly the incidence of heat wave in Melbourne in 2009, it is important to integrate the theoretical climatic knowledge into future planning schemes. Therefore this study aims to examine the thermal consequence of implementing the structural plans in one of the rapidly growing neighbourhoods located in the north part of Melbourne' CBD, through simulation.

ENVI-met 3.1Beta 5 will be used as a modelling system to simulate the study area on an extremely hot summer day. ENVI-met is a grid-based CFD three-dimensional (3D) model that performs micro-scale simulations with a spatial resolution typically ranging between 0.5 m and 10 m with 10 s time frames (Bruse, 2004). The findings of this study provide a foundation for developing the future urban growth policies with taking a climate-conscious urban design approach. An approach in which the wellbeing and pedestrian thermal comfort will be further guarantied.

2. Literature review (Pedestrian thermal comfort and urban design)

Thermal comfort refers to "the condition of the mind that expresses satisfaction with the thermal environment" (Ashrae, 1997). Some scholars define this concept as "the absence of thermal discomfort, in which individuals feels neither too warm nor too cold" (McIntyre, 1980). Pedestrian summertime thermal comfort and mortality rate are strongly compromised by the global climate change and the heat island effect (Santamouris et al., 2007). Uncomfortable outdoor environments and extreme heat adversely affect public health, particularly that of the elderly who are more vulnerable to heat (Loughnan et al., 2010).

Outdoor thermal comfort is determined by meteorological factors (i.e., air temperature, humidity, radiation, and air movement), personal factors (i.e., insulation and clothing value), and rate of metabolism, which in turn is affected by body shape, age, and gender. These factors affect thermal comfort by altering the heat exchange process of the human body through convection, conduction, and radiation.

The relationship between urban design parameters and pedestrian thermal comfort has been more under investigation recently (Sanaieian et al., 2014). Some studies have enabled the development of technological measures to create thermally comfortable urban area through modifying the grey and green infrastructure (Santamouris et al., 2007; Akbari and Levinson, 2008; Santamouris et al., 2012). Among these mitigation techniques, urban geometry manipulation and street-level urban greening are identified as the most effective design strategies in ameliorating the outdoor thermal comfort at pedestrian level.

2.1. Grey infrastructure affecting pedestrian thermal comfort

The Physiologically Equivalent Temperature (PET) is defined as the "air temperature at which the heat balance of the human body is maintained with core and skin temperature equal to those under the conditions being assessed" (Höppe, 1999). PET is based on the Munich Energy- Balance Model for Individuals (MEMI) that defines the balance equation of the human body as:

$$M + W + R + C + E_D + E_{Re} + E_{Sw} + S = 0$$

where M is the metabolic activity, W is the physical work output, R is the net radiation of the body, C is the convective heat flow, E_D is the latent heat flow to evaporate water into water vapour diffusing through the skin, E_{Re} is sum of heat flows for heating and humidifying the inspired air, E_{Sw} is the heat flow due to evaporation of sweat and S is the storage heat flows for heating or cooling the body mass.

Aspect ratio (H/W) is the first and foremost parameter that determines the geometry of an urban area. This concept pertains to the ratio between the average height (H) of the canyon walls and the canyon width (W) (Oke, 1988). Several studies reported a clear correlation between pedestrian thermal comfort and aspect ratio and emphasized the need to consider the possible consequences of aspect ratio on thermal radiation in cities (Lin et al., 2010). A study in Campinas, Brazil, quantified the variation of thermal comfort that resulted from changing H/W ratio by creating a 3D street canyon model using RayMan Pro and found that increasing the amount of shade on pedestrian areas and façades could help mitigate bio climate thermal stress, especially in canyons with H/W ratio of less than 0.5 (Abreu-Harbich et al., 2013).

Street orientation is another important parameter that defines the level of solar access to the streets, the air circulation in urban canyons and therefore in determining the thermal comfort in sidewalks (Yang et al., 2013). In the Mediterranean coastal region of Israel, N–S-oriented streets with trees were cooler by 0.64 K than E–W-oriented canyons during the hottest hour of the day (15:00 h) (Shashua-Bar and Hoffman, 2004). The effect of canyon orientation was more perceptible in deep and narrow canyons than in shallow and wide ones. Kruger showed that mutual shading on east and west walls is the main reason for the cooler daytime air temperatures in N–S-oriented canyons during morning and afternoon (Krüger et al., 2010). In a similar study in a semi-arid climate of Campinas, Brazil, NE–SW-oriented streets demonstrated the lowest PET values (Abreu-Harbich et al., 2013).

Sky view factor (SVF) is the third important parameter in determining the urban geometry. SVF is defined as "the ratio of the amount of the sky which can be seen from a given point on a surface to that potentially available (i.e., the sky hemisphere subtended by a horizontal surface)" (Oke, 1987). This parameter is a dimensionless number ranging from 0 to 1 and is also an important element in generating and controlling the heat island effect (Oke et al., 1991). Studies investigating the effect of SVF on the thermal condition of urban canyons have shown that lower daytime air temperature (Cool Island) and higher night-time air temperature (heat island) are usually correlated with lower SFVs (Unger, 2004; Svensson, 2004).

SVF also defines the level of air velocity. Previous studies have shown that SVF could indicate the thermal-buoyancy-driven airflow rate under weak wind environments as determined by solar radiation heating. The empirical data from extensive field measurements in Shanghai were used to examine the micro-scale effect of urban form on the potential ventilation in outdoor environments and highlighted the significant role of "enclosure" or SVF in developing pedestrian-level wind velocity. The study showed that 10% increase in SVF would increase the wind speed at the pedestrian level by 8% (Yang et al., 2013).