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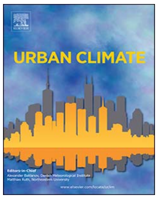

Development of the VTUF-3D v1.0 urban micro-climate model to support assessment of urban vegetation influences on human thermal comfort

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ABSTRACT

With urban areas facing longer duration heat-waves and temperature extremes from climate change and growing urban development, adaptation strategies are needed to protect city residents. Examining the role that increased tree cover and water availability can have on human thermal comfort (HTC) is needed to help guide the development of thermally comfortable cities. To inform planning, modelling tools are needed that provide sufficient resolution to resolve urban influences on HTC and the ability to model important physiological processes of vegetation. To achieve this, a new micro-scale model, VTUF-3D (Vegetated Temperatures of Urban Facets) has been developed. In it, offline modelling of individual items of vegetation is performed using the MAESPA process-based tree model (Duursma and Medlyn, 2012) (a model that can model individual trees, vegetation, and soil components), and integrated into the TUF-3D (Krayenhoff and Voogt, 2007) urban micro-climate surface energy balance (SEB) model. This innovative approach allows the new model to account for important vegetative physiological processes and shading effects, using configurable templates to allow representation of any type of vegetation or water sensitive design feature. This work enables detailed calculations of surface temperatures (T_{sfc}), mean radiant temperature (T_{mrt}), and a HTC index, the universal thermal climate index (UTCI), across urban canyons. This study presents an overview of VTUF-3D. Also presented are two evaluations of VTUF-3D. The first evaluation compares modelled surface energy balance fluxes to observations in Preston, Australia (Coutts et al., 2007). The second evaluation compares spatial and temporal predictions of T_{mrt} and UTCI to two observed street canyons in the City of Melbourne (Coutts et al., 2015b). The VTUF-3D model is shown to perform well and is suitable for use to examine critical questions relating to the role of vegetation and water in the urban environment in support of HTC.

1. Introduction

Urban areas are facing a growing number of challenges. Cities are now home to the majority of the world's population and trends will result in further growth (UNDESA, 2015; WHO, 2016). To accommodate increasing urban populations, cities are expanding (Seto et al., 2011) and densifying (Byrne et al., 2016; Ruth and Coelho, 2016; DSE, 2002), leading to loss of urban green spaces (Hamin and

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Nomenclature

α_{veg}	shortwave albedo of vegetation
α_g	globe albedo (=0.05)
α_{sfc}	surface albedo (=0.15)
ϵ_{veg}	longwave emissivity of vegetation
ϵ_a	longwave emissivity of the atmosphere
ϵ_g	globe emissivity (=0.95)
σ	Stefan-Boltzmann constant ($=5.67 \times 10^{-8}$ W m^{-2} K^{-4})
θ	solar zenith angle
A	surface area of a sphere of diameter D, of value 0.15 m, ($=\pi 0.15^2$ m^2)
d	index of agreement ($0 \leq d \leq 1$)
f_{dir}	fraction of the total horizontal solar irradiance, S, due to the direct beam of the sun
h	convective heat transfer coefficient (W m^{-2} K^{-1})
h_i	heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity of the fluid (i.e. air) (W m^{-1} K^{-1})
$K\downarrow$	downward shortwave radiative flux density (W m^{-2})
$K\downarrow_{dif}$	domain-level incoming diffuse shortwave (W m^{-2})
$K\downarrow_{dir}$	domain-level incoming direct shortwave (W m^{-2})
$L\downarrow_{i,sky}$	initial incident sky-derived longwave (W m^{-2})
$L\downarrow$	downward longwave radiative flux density (W m^{-2})
Q^*	net radiation flux density (W m^{-2})
Q^*_{veg}	calculation of vegetation net radiation flux density (W m^{-2})
$Q_{E,veg}$	calculation of vegetation latent heat flux (W m^{-2})
Q_E	latent heat flux (W m^{-2})
Q_F	anthropogenic heat (W m^{-2})
$Q_{G,veg}$	calculation of vegetation ground heat storage (W m^{-2})
Q_G	ground heat storage (W m^{-2})
$Q_{H,veg}$	calculation of vegetation sensible heat flux (W m^{-2})
Q_H	sensible heat flux (W m^{-2})
$RMSE$	root mean square error
S	horizontal solar irradiance (W m^{-2})
T_a	dry bulb air temperature (K)
T_{can}	canyon air temperature (K)
T_g	globe temperature (K)
T_{mrt}	mean radiant temperature (° C)
$T_{sfc,veg}$	vegetation surface temperature (K)
T_{sfc}	surface temperature (K)
$UTCI$	universal thermal climate index
ws_{cm}	wind speed (cm s^{-1})

Gurran, 2009; Coutts et al., 2007). In these increasingly urbanised areas, the removal of vegetation, combined with rapid stormwater removal and possibly restricted irrigation during drought conditions, can leave urban landscapes water starved. Urban development that does not consider the implications on urban climate, risks intensifying urban heating and compromising the thermal comfort of city residents. In addition, climate trends point towards increasing average and extreme temperatures (Alexander and Arblaster, 2009; IPCC, 2013). These trends are concerning given the growing understanding of the impacts on human health of extreme temperatures (Katsouyanni et al., 1993; Nicholls et al., 2008; Loughnan et al., 2010) and demographics that are shifting towards a more elderly population (Cohen, 2003; Federal Interagency Forum on Aging-Related Statistics, 2016) that is particularly vulnerable to extreme heat, and leave those in urban areas in an increasingly dangerous position. In coming years, cities and their residents will need to adapt to these challenges.

Incorporating more vegetation and water into urban areas can effectively mitigate extreme urban temperatures at local to micro scales (Tsiros, 2010; Shashua-Bar et al., 2010; Spangenberg and Shinzato, 2008; Coutts et al., 2012). Shading and evapotranspiration are cited as the main drivers of these cooling effects (Bowler et al., 2010). The degree of cooling effects are variable however, and depend on factors such as vegetation density (Hall et al., 2016; Bodnaruk et al., 2017), street orientation and aspect ratio (Ali-Toudert and Mayer, 2006; Thorsson et al., 2011), and amounts of irrigation used (Jenerette et al., 2011). Trees in particular provide a strong benefit for HTC during the day, especially those with large, dense canopies that provide shade and are well irrigated to promote transpiration (Coutts et al., 2015b; Huang et al., 2008; Yılmaz et al., 2007; Shashua-Bar and Hoffman, 2000), with possible additional side benefits of reduced energy usage (and associated emissions and anthropogenic heat) for cooling (Donovan and Butry, 2009; Rosenfeld et al., 1996; Simpson and McPherson, 1993) by strategically placed trees. Water sensitive urban design (WSUD) presents an opportunity to capture and retain stormwater in urban areas using engineered and natural features (trees, vegetation, and substrate) to capture, filter, and store water as an additional urban water source (Wong and Brown, 2009). A more focused effort in using trees and WSUD for urban climate benefits can deliver improvements to human thermal comfort (HTC) (Coutts et al., 2012).

While the benefits of urban vegetation and water are well understood in the climate community, uptake and application of knowledge in urban planning is lacking. Bowler et al. (2010) suggests that the current research does not demonstrate exactly how urban greening should be implemented in terms of abundance, type, and distribution. A suitable modelling tool is needed to provide solid quantitative assessments of the effectiveness of trees and water in terms of heat mitigation, across contrasting micro-scale urban environments, and therefore provide guidance on how to most effectively use trees and WSUD for improved HTC.

A suitable modelling tool for these assessments needs to resolve detailed temperature gradients (as well as wind speed and humidity in order to calculate HTC) across a modelled urban canyon, requiring micro-scaled resolution climate modelling. In addition, modelling needs to incorporate important cooling mechanisms of evapotranspiration and shading. Accounting for these effects requires proper modelling of vegetation, including vegetation physiology to estimate accurate latent energy fluxes and the soil-vegetation-atmosphere pathway critical for vegetation and WSUD assessments within the urban canyon. Models such as SOLWEIG (Lindberg et al., 2008) and RayMan (Matzarakis et al., 2007, 2010) resolve at a suitable scale and generate useful insights into mean radiant temperatures in urban areas (Chen et al., 2014), only capture the radiation shading effects of vegetation, and are unable to account for the effects of water and evapotranspiration. At the other end of the complexity spectrum, a number of models, primarily