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Evaluation of canopy-layer air and mean radiant temperature simulations by a microclimate model over a tropical residential neighbourhood

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ABSTRACT

The performance of a 3D urban microclimate model (ENVI-met Version 3.1) is evaluated with data collected during mostly clear and calm conditions in a compact low-rise residential neighbourhood of tropical Singapore. Observations are obtained from seven canopy-layer air temperature, T_a, sensors at 2 m above ground, including a fully equipped microclimate station measuring mean radiant temperature, *MRT*, at 1.1 m above ground. The model is capable of capturing the spatial variability across all stations during most of the eight simulation days. Spatially-averaged T_a predictions are closer to the observations during wet (based on five simulation days) compared to dry (three days) periods. Daytime model performance for *MRT* is variable but peak values are well predicted. Systematic errors dominate most simulations. The present model evaluation metrics are smaller than reported in similar work, which is likely due to the more accurate determination of model input variables using locally measured soil relative humidity and leaf area density profiles. A modification to how the model calculates *MRT* also helps to improve its daytime performance. Finally, the model is used to predict the effect of five temperature mitigation/planning strategies. The varying results highlight the micro- and bioclimatic complexities inherent in a heterogeneous urban system, with no one scenario providing consistent cooling throughout both day- and nighttime. Overall the present results suggest that ENVI-met is a useful planning tool for assessing T_a and daytime extremes in outdoor thermal comfort, but the model requires detailed local information for proper initialization and awareness of its limitations.

1. Introduction

Urbanization radically alters the physical environment from its natural state, and has inadvertent albeit important environmental consequences. The aerodynamic, thermal, radiative and hydrological processes characteristic of natural environments are changed through modifications of surface morphology, introduction of artificial surfaces, reduction in vegetation cover and emission of urban pollutants [1]. As a consequence cities experience elevated air temperatures and have a different thermal regime from that of surrounding rural, undeveloped areas [2]. Such elevated temperatures are clearly undesirable in cities in the humid tropics where the combination of high air temperature and humidity, intense solar radiation and low wind speed results in thermally stressful conditions throughout the year [3]. Some of the consequences of the additional urban warmth superimposed on already high mean air temperatures include a reduction in outdoor thermal comfort (OTC) with detrimental impacts on human health and mortality, or an increase in demands for air conditioning and hence energy usage. A global climate model with an embedded urban model further predicts that the tropics will experience the greatest increase in number of high-heat-stress nights under a global warming scenario [4]. Urban climate research should therefore assume a high priority in the humid tropics where rapid urban growth is occurring [5] and the improvement of OTC should be a key planning consideration [6].

Microclimate models are useful tools to predict climatic features of the urban environment and they provide an important means of assessing feedback relationships between urban modifications and the climate, and vice versa [7]. These models offer the flexibility of evaluating a wide range of urban configurations for a specific purpose or to answer explicit urban planning and design questions. If

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the models are accurate, they provide an alternative to time-consuming and costly field measurements, and are the only way to predict future climate conditions arising from planning interventions. The choice of the most appropriate model depends on the research question asked. Several models such as RayMan [8], SOLWEIG [9], SkyHelios [10] and ENVI-met [11] are capable of predicting biometeorologically relevant variables at very high spatial resolution. ENVI-met remains the most widely used model, perhaps because of its longer existence and relative ease in operation.

ENVI-met has been used to examine the urban microclimate or impacts of typical UHI mitigation strategies on air temperature and thermal comfort in mostly low-rise residential neighbourhoods. Studies have been conducted in humid (sub)tropical cities such as Colombo, Sri Lanka [12,13], Dhaka, Bangladesh [14], Shanghai, China [15], Hong Kong [16] or Putrajaya, Malaysia [17], and hot/dry cities such as Fez, Morocco [18,19], Melbourne, Australia [20], Phoenix, USA [21–25], Lecce and Rome, Italy [26,27]. The most recent version of ENVI-met has been extensively evaluated over sub-tropical Guangzhou, China [28] and was also tested in Rome [27].

An important, yet often neglected part of modeling is the proper initialization and evaluation of models [2]. Without proper evaluation to test the reliability of its output, the application of a model is questionable and it cannot be used as a trustworthy guide to policy formulation [29]. Although ENVI-met has been widely applied, its evaluation has not always been rigorous and until recently focussed primarily on canopy-layer air temperature (T_a). Some studies found that ENVI-met underestimates (overestimates) daytime (nighttime) T_a [12,21,22], others reported overestimation of daytime (or part thereof) T_a [15,24], and yet others have found underestimation of both day- and nighttime T_a [13,20]. Most research evaluates predictions for a single day or a few hours only [13,14,16,21,22], and only very few studies investigate the performance to assess the small-scale spatial variability the model is designed to predict [22,24,28]. With the exception of [24,28] most work also did not obtain site-specific initialization data (e.g. soil moisture and temperature) and instead used values from outside the modeling domain (e.g. from weather stations at nearby airports). In addition, there has been limited application of the model to hot and humid climates with only three studies carried out in Colombo, Dhaka and Putrajaya (see above). Furthermore, evaluations of other variables such as the biometeorologically relevant *MRT* are non-existent despite its use as an indicator of thermal comfort.

In order to address some of the existing research gaps, the first objective of the present study is to critically evaluate the accuracy of ENVI-met 3.1 in predicting the temporal dynamics of T_a and *MRT* during different seasons over a compact low-rise residential neighbourhood located in humid tropical Singapore. Since the model was initially developed for temperate climates, it cannot be assumed *a priori* that the default input parameters are applicable in the present context. The study area is therefore carefully represented in ENVI-met using selected site-specific input data from field measurements. Although an updated, improved ENVI-met Version 4 [30] has recently been released, the present research provides an assessment of past studies that have used the same version employed herein. Further, since some aspects of the model have not been updated in the new version (e.g. the soil model) any additional insight even from an older version will still be useful. The second objective is to estimate how T_a will be influenced by the implementation of common UHI mitigation strategies which include the modification of albedo, vegetation and building heights.

2. Methods

2.1. Study area

Singapore is a low-lying island city-state located between 1°09 N to 1°29 N, and 103°36 E to 104°25 E, just south of Peninsular Malaysia. Owing to its geographical proximity to the equator, Singapore has a tropical rainforest climate (Köppen classification, *Af*), which is characterized by uniformly high temperatures (annual mean: ~27 °C) and abundant annual rainfall (~2340 mm). Mean monthly rainfall peaks during the northeast (NE) monsoon period (>250 mm month^{-1}) between December to early March while the southwest (SW) monsoon period (June–September) typically experiences drier than average conditions (~150 mm month^{-1}). Wind speed measured 10 m above surface is generally low (1.3–2.8 m s^{-1}). During the remaining months of the year (i.e. intermonsoon, IM, periods), surface winds are light with variable directions and possibly influenced by land and sea breezes. Synoptic weather conditions vary little across the island due to Singapore's small size and lack of topography, although isolated, small convective systems can result in localized rainfall. However, heterogeneity in the urban landscape (e.g. downtown central business district vs. residential neighbourhoods) gives rise to micro-scale and local differences in temperature and moisture regimes [6,31]. The combination of high T_a, relative humidity (*RH*) and low surface wind speeds has important consequences for thermal comfort in the tropics which is likely made worse by the UHI given Singapore's extensive urbanization [6,32].

The present study area is located in the low-density residential neighbourhood of Telok Kurau (TK) ~3 km north of Singapore's south-eastern coastline. A ~23 ha (548 × 428 m) area constitutes the model domain (Fig. 1) which is characterized by densely-placed low-rise buildings with mean (z_{mean}) ± 1 standard deviation, median (z_{median}) and maximum (z_{max}) building heights of 10.6 ± 4.7, 9.0 and 25.0 m, respectively. Buildings are a mixture of semi-detached houses (duplexes), terrace (row) houses and individual bungalows, interspersed with several taller (up to five storey high) condominiums. The compact low-rise area corresponds to Local Climate Zone (LCZ) 3 [33]. Although TK is not representative of the more common high-rise neighbourhoods in Singapore, it is undergoing rapid transformation where new condominium developments are replacing low-rise houses. Resident population density is ~7500 persons/km^2 and hence similar to the city-wide average.

The main street (Telok Kurau Road) traversing the study area has a SE–NW orientation and runs along the western edge of the model domain (Fig. 1). Secondary streets connected to the main street are orientated WSW-ENE. Tertiary streets perpendicular to the secondary streets are typically cul-de-sacs leading to residential homes and have similar orientations as the main street (NW-SE). Both main and secondary streets are lined with shade trees with heights (z_{tree}) ranging between 3.5 and 11.2 m. Individual houses usually have small gardens planted with turf grass, shrubs and small trees. There are several recreational grass fields with a combined size of ~1.2 ha in the study area. Slightly more than half (~1.1 ha) of an adjacent park (~1.8 ha) to the NE is also included in the model domain (Fig. 1). The study area is dominated by impervious surfaces, with buildings covering 39.8%, pavements 35% and roads 8.5% of the surface. Vegetation comprises 15.7% of the area where 7.6% and 8.1% are grass and trees, respectively. Other uses (water bodies and gravel) constitute only ~1%. The TK neighbourhood has recently been used in a number of urban flux studies which provide more detail on the site characteristics [34,35].