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Impact of urbanization level on the interactions of urban area, the urban climate, and human thermal comfort

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A B S T R A C T

One significant effect of urbanization is the modification of natural surfaces, local environment, and thermal comfort. Farmland and agricultural land in Klang Valley conurbation, Malaysia have been replaced with engineered surfaces and infrastructures to accommodate the rapid population growth witnessed in the past decades. To understand the current environmental conditions of the conurbation, numerical Weather Research and Forecasting (WRF) model coupled to the Urban Canopy Model (UCM) was used. A model evaluation conducted against a network of observations showed an overall good performance of the model in predicting near-surface meteorological parameters. Also, an examination of spatiotemporal variability of urban parameters revealed a diurnal dependence of human physiological thermal conditions on urbanization level. A maximum urban heat island intensity (UHII) of ~2.64 °C was observed. In an effort to investigate the effect of urbanization level on the extremities of urban climatic conditions, two different experiments with varying urban/vegetation fractions were further simulated. The latter results indicate that urbanization level has a significant effect on the extremities of urban climatological parameters and spatial extent of the induced impacts. Furthermore, the effect of urbanization level on the mean urban outdoor thermal discomfort (UOTD) level was significant (with an increase of 0.7 °C, 0.64 °C and 0.04 observed) for temperature humidity index (THI), effective temperature index (ETI) and relative strain index (RSI), respectively. However, a non-significant (at 95% level) effect of urbanization level on the extremities of UOTD indices was observed.

1. Introduction

Malaysia has witnessed an increase in urban expansion during the past three decades. 30–40% of the reported expansion occurred within the Klang Valley, sometimes referred to as Greater Kuala Lumpur, GKL (Masron et al., 2012; Yaakob, Masron, & Masami, 2010). GKL covers 2.5% of Malaysian total landmask, yet it is home to 26% of the country's population and contributes about 41% of the national GDP. The observed economic and human capital development due to urbanization of the Valley has led to a surge in population density and urban growth footprints. This in effect has led to phenomena such urban heat island (UHI) and urban outdoor thermal discomfort, UOTD, (Morris, 2016; Morris et al., 2016; Shaharuddin, Noorazuan, & Takeuchi, 2014). UHI phenomenon and UOTD accompany the urbanization processes involved in the conversion of natural, rural and agricultural land to urban surfaces

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(Wang et al., 2016). The conversion processes create an urban canopy layer (2-m) of buildings and changes in radiation, dynamic and thermal characteristics of the underlying surfaces. These changes modulate imbalances in the land use/land cover (LULC) of urban and surrounding areas. This, in turn, induces a horizontal gradient of surface exchange of momentum, heat, water vapor, and modification of surface energy partitioning and urban energy balance. Furthermore, the consequential decrease in surface moisture availability and increase in air temperature will, therefore, increase the UOTD level in the urban areas.

The influence of urbanization is not restricted to the neighborhood and local scales only but extends regionally (Zhang et al., 2010; Zhang, Wen & Jang, 2010). *In-situ* and statistical methods, especially correlation and regression, have been used in different studies to evaluate the impact of urbanization on surface UHI and human UOTD level. Also, remote sensing techniques have been employed to investigate the effect of urbanization and the associated impacts on the urban environment and human comfort (Wang et al., 2016). *In-situ* data collection, especially permanent meteorological station data, offer high temporal resolution and long-term coverage but lacks spatial details. This limitation can be corrected by moving observation, but do not provide a synchronized view over the city. Moreover, the difficulty to evaluate and separate influence of urbanization from other impacts of LULC changes, such as spatial and temporal characteristic of plants emissions which is correlated to temperature, on the urban environmental conditions through observations is a major setback using the *in-situ* approach. In the case of remote sensing techniques, land surface temperature (LST) derived from thermal infrared remote sensed images are correlated with changes in LULC, built-up areas, and vegetation index in urban cities (Azevedo, Chapman, & Muller, 2016; Rotem-Mindali et al., 2015). Skin surface temperature (LST) and near-surface temperature/2-m temperature (T2m) are although closely related; they are different because T2m correlates more with human thermal comfort (Cui & de Foy, 2012; Gallo et al., 2010). Nevertheless, remote sensing techniques can only measure the LST. For the statistical technique, the limitation comes in describing the spatiotemporal variations of UHI generation and evolution (Voogt & Oke, 2003) over an urban area. Thus, the needs for an alternative approach – Weather Research and Forecasting (WRF) Model – which complements and overcome the inherent limitations with other methods. The Weather Research and Forecasting (WRF) model, a next-generation mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting needs (Skamarock & Klemp, 2008), is an alternative approach to investigate the effect of urbanization on urban climate and UOTD (Conry et al., 2015; Morris, Chan & Ooi et al., 2016). The WRF model can describe the generation, patterns, development and the associated factors of UHI (Wang et al., 2016) using the T2m.

The capability of the WRF has been highlighted to investigate the impact/interactions of LULC, variations in UHI and urban climatic parameters, and planetary boundary layer (PBL) evolution in different cities and some urban conurbations, such as Taipei (Lin et al., 2008), Houston (Chen et al., 2011), Tokyo (Kusaka et al., 2012), Athens (Papangelis et al., 2012), Beijing (Wang et al., 2016), and Putrajaya (Morris et al., 2015; 2015; Morris, Chan & Salleh et al., 2016). Most studies on urban climate have been focused on urbanization and UHI, and less has been studied on the impact/interactions of urbanization with the UOTD, especially in the tropics. Due to the complex and unique identity of each urban area, which determines the resulting urban climate, generalizability of scientific knowledge on urbanization studies has become difficult. Moreover, it is expected that urban temperatures in the tropics would show more extremes relative other climate zones because of high intensity of solar radiations due to proximity to the equator, however, urban climate phenomena, such as UHI and OUTD, do not depend only on the high intensity of solar radiations which distinguished the tropics from other regions, but also, on urban morphology and meteorology of the area. In this study an investigations is conducted in a tropical, country, Malaysia to understand the physics and dynamics of urbanization and the interactions with the local urban climate and human thermal comfort in outdoor urban spaces.

Jauregui (1958) and Galindo (1962), who investigated the local increase in turbidity and observations of global radiation in Mexico City, were the first possible published literature on tropical urban climate studies. However, their efforts were not replicated in other cities of the tropics in the decades before the 2000s. Nevertheless, from the 2000s, few similar studies such as Chow and Roth (2006) in Singapore, Balogun (2012) in Nigeria, Duarte et al. (2015) in Brazil, and Morris et al. (2015) in Malaysia, have been conducted in the tropics. Like the urban climate studies, few investigations in the tropics (Eludoyin et al., 2014; Ghaffarianhoseini, Berardi, & Ghaffarianhoseini, 2015; Makaremi et al., 2012; Yang, Wong, & Jusuf, 2013) have looked at the prevailing thermal comfort of urban cities, among which little is known on the relationship between urbanization, urban climate and UOTD level in the region. This scenario is often complicated by the limited availability of meteorological stations in the tropics (Morris, 2016).

In this study, the Advanced Research WRF (ARW) version 3.5.1, coupled with the new-generation Urban Canopy Model (UCM) and Noah Land Surface Model (Noah-LSM), WRF/Noah/UCM, is used to model the urbanization processes using a three one-nested domain downscaling approach to investigate the urban climate and UOTD of a tropical conurbation, GKL, Malaysia. The coupling of the single-layer UCM with the Noah-LSM completes the urban surface energy balance by calculating fluxes from the vegetated portion of the urban surface in a given grid cell. Furthermore, the influence of LULC changes caused by urbanization and urban size on the prevailing thermal conditions of the Valley is also examined. Findings from this study will benefit urban planners, for both retrofit and future urban planning, and could be adapted to other tropical cities.

2. Case design

2.1. Study area

GKL is an urban conurbation in Western Malaysia. It encompasses the federal capital territory, Kuala Lumpur; the newly developed administrative capital, Putrajaya; and the adjoining suburbs, cities, and towns in the state of Selangor. In total, the GKL comprises of 40 districts. Geographically, the GKL is delineated to the North and North-East by the Titiwangsa Mountains and Strait of Malacca to the West (Fig. 1). The climate of the region is characterized by equatorial climate type Koppen *Af* (Kottek et al., 2006). GKL is typified by tropical rainforest and near-uniform monthly mean temperature and high relative humidity (RH) (MMD, 2015). The conurbation drives the Malaysian industry and commerce, and is home to about 7.6 million people (26% of the country's population), and contributes about 41% of the country's gross domestic product, GDP (Gambero, 2013). According to the Malaysian Department of Statistics, the area recorded the highest rate of urbanization in the past decade. GKL has a developed urban morphology compare with the surrounding states.

The GKL is situated few degrees north of the equator and lies in the western part of the Maritime Continent of Southeast Asian