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Numerical study on effect of urban heating on local climate during calm inter-monsoon period in greater Kuala Lumpur, Malaysia

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ABSTRACT

The Weather Research and Forecasting (WRF) mesoscale model is used to study the effect of urban heating on the local climate of the largest urban agglomeration of Malaysia, Greater Kuala Lumpur (GKL) during a period of weak synoptic forcing. Urbanization has induced a modelled daily mean urban heat island (UHI) intensity of 0.9 °C with a more severe heating (1.9 °C) at night. The diurnal wind field of GKL is greatly affected by the circulation of land/sea breeze. The immense heat generated in the city accelerates the moisture-bearing sea breeze during the day and the induced vertical lifting simultaneously creates a conducive environment for convective precipitation on the upwind region. The urban heating effect and surface roughness weakens the evening flow circulations in the region and potentially inhibits dispersion of heat and atmospheric pollutants. Simulation of UHI phenomenon is especially sensitive to the characterization of urban grids through sensitivity evaluation of numerous land use maps and urban canopy model (UCM) settings. When compared to observations, the WRF model best captures the urban heating phenomenon with updated land use map and calibrated single layer UCM, while the simple bulk UCM setting performs better than the default complex single layer UCM.

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1. Introduction

Among the 3.9 billion global urban residents, more than half settles in Asia, one of the less urbanized region in the world (United Nations, 2014). These cities are projected to expand by 16% before 2050 to accommodate the urban rush. The demographic shift from countries to cities has caused the overcrowded metropolitan to be ubiquitously hotter than countryside; this phenomenon is coined as "Urban Heat Island" (UHI) (Oke and Maxwell, 1975). The formation of urban heating effect is primarily stemmed from the introduction of impervious man-made surface and structure made up of engineered material with dissimilar thermal and radiative characteristics (Jusuf et al., 2007; Oke, 1987). These strong and durable man-made materials, especially concrete and asphalt are of high thermal conductivity to absorb and store massive heat during the day (Akbari et al., 2008; Oke and Maxwell, 1975). Unlike mature vegetated surfaces, the limited moisture content in urban surface impedes latent heat dissipation causing the ground to cool down at a slower rate (Dimoudi and Nikolopoulou, 2003; Gao and Jia, 2013). The re-radiated longwave radiation hence increases the nocturnal temperature within the densely-packed urban canopy (layer between the ground up and average height of the buildings) with low sky-view factor (Grossman-Clarke et al., 2008). The severity of UHI is often bolstered by the local topographic circulation (Giovannini et al., 2013; Lin et al., 2008; Steyn, 1996) and synoptic weather condition (Chow and Roth, 2003; Lai and Cheng, 2009; Morris et al., 2001).

Comprehensive study on the implication of land use change on urban heating requires knowledge of the spatial extent, hence in-situ measurement approach with their inherent limitation on spatial distribution is a less preferable alternative (Mirzaei and Haghighat, 2010; Santamouris, 2015). The numerical methods in combination with the land use information from the remote sensing images are often adopted to address spatio-temporally the heat accumulation scenario (Freitas et al., 2006; Li et al., 2016; Miao et al., 2009; Zhang et al., 2011). Also, with the versatility of model settings, the different physical properties of land use can be investigated for their contribution to the urban heating, for example impervious fraction of surface (Giovannini et al., 2013; Grimmond et al., 2011; Li et al., 2013a), surface albedo (Akbari and Konopacki, 2004; Fallmann et al., 2016; Taha, 1997), roughness length (Carraca and Collier, 2007; Loughner et al., 2012; Zhong and Yang, 2015), anthropogenic heat (Giovannini et al., 2013; Li et al., 2013b; Wang et al., 2015a), urban morphology and building materials (Giovannini et al., 2013; Grimmond et al., 2011; Sharma et al., 2016b).

Kataoka et al. (2009) observed that cities in South East Asia (SEA) have experienced the most rapidly increasing urban heating for the past 40 years compared to the rest of the megacities in East Asia due to its booming population (Tran et al., 2006). However, the urban heat research studies in the South East Asia is still lacking (Roth, 2007) despite the availability of numerous weather simulation models developed for urban scale (Grimmond et al., 2011). The hydrological implication of land use change on the urban-induced precipitation and flooding of the river city, Can Tho, Vietnam was studied with the combination usage of mesoscale weather model (WRF) with land use projection model and an urban flooding model (Huong and Pathirana, 2013). The island city, Singapore have shown the relative influence of anthropogenic heat emission and reduction in evapotranspiration of the urban surfaces on the local wind field and precipitation pattern in the WRF ensemble study (Li et al., 2016; Li et al., 2013b). Several efforts have verified the feasibility of garden city concept in the new administration center of Malaysia, Putrajaya which the urban heating is offset by the heterogeneous mixing of vegetation cover within the city (Morris, 2016a; Morris et al., 2015). Although the WRF model is well verified with measured data in most of these studies, we note that the scientific ground of some essential parameterization schemes is not given much attention. Lack of site-specific information, especially studies down to the fine urban scale of few kilometers, might affect model performance when use in combination with the overly complicated parameterization scheme (Grimmond et al., 2011; Liao et al., 2014). The model sensitivity analysis and evaluation therefore become more pressing with the rapid growing application of the numerical model despite being in its induction stage in the SEA region.

Greater Kuala Lumpur (GKL) is the most urbanized conurbation of Malaysia (DOS Malaysia, 2011). The 2785 km^2 area covers two administrative center, namely Kuala Lumpur WP Putrajaya with their peripheral local districts, including Gombak, Hulu Langat, Klang, Petaling Jaya and northern part of Sepang as shown later in Fig. 3. Past studies reported that the urban core of GKL experienced higher temperature up to 5.5 °C than its rural park and this city is on average 3.9 °C hotter than other cities in Malaysia (Elsayed, 2012; Ng et al., 2005; Sani, 1986). Recent numerical effort has also found that higher mean daily temperature modelled