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Numerical study on the urbanisation of Putrajaya and its interaction with the local climate, over a decade

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ABSTRACT

Land use and land cover changes, urban warming and changes in urban climate variables of a given location are some of the profound signatures of urbanisation. Putrajaya is a planned city built from a formerly vegetated farm and agricultural lands to a modern urban city. This study aims to investigate the chronological local urban climate changes that have taken place over a decade (1999–2011) of urbanisation using the NCAR Weather and Research Forecasting (WRF) model coupled to a numerically proven land surface and urban canopy model (NOAH LSM/UCM). Up-to-date and accurate land cover dataset of the region implemented for each year is derived from LANDSAT images. Model results are evaluated against a network of observational studies in the region. 2-m air temperature, wind speed, relative humidity, planetary boundary layer height and urban warming of the area in each of the considered years are carefully examined. Solar radiation, urban surface induced variations in the urban surface energy balance components, and variations of the study area urban climatic variables are also investigated. Model results demonstrate good correlation and agreements with the observed data, with 2-m air temperature performance observed to be better relative to other variables evaluated. Results show that 2-m temperature of the area is increasing at the rate of 1.66 °C per decade, while the prevailing urban heat island intensity (UHII) of the area is ~2.1 °C. The urban climate prognostic and diagnostic variables show good correlations with the urban surface modifications of the area from the original natural surfaces, except for wind speed which shows less variability to urbanisation. Furthermore, formation of urban cool islands is also noticed for 1999, 2007, and 2011. Near-uniform net all-waves radiations of the different years experimented conform to tropical city low climatic variability. Finally, the thermal conditions of the area exhibit spatial and temporal variations heavily induced by urbanisation.

1. Introduction

Human continual strive for better living conditions have caused rapid urbanisation and expansion of human inhabited areas, which have replaced previously natural farmland and vegetation with engineered surfaces. This has caused changes in the environment, prominent of which are the canopy-layer temperature and urban heating (Landsberg, 1981). The under-

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lying land use and land cover changes caused by urbanisation has impact on the thermal and dynamic properties of land surfaces (K. Zhang et al., 2010; N. Zhang et al., 2010). Meanwhile increased urban environmental pollution associated with urbanisation is caused by rural–urban migration prompted by search for better living conditions and daily routine to sustain the urban population. The urban population needs huge urban energy resources to maintain the urban metabolism (Kennedy et al., 2007; Wolman, 1965). However, consumption of urban heavily needed resources comes with damning consequences on the environment through releases of anthropogenic heat (AH) and associated disposable human wastes (Marais et al., 2014).

Engineered materials and impervious surfaces such as asphalt, concrete, bricks, stones and bitumen, roads, low and high rise buildings, pavements, sidewalks and bridges (Wijeyesekera et al., 2012), have immense contributions to the alteration of urban surface energy balance (Arnfield and Grimmond, 1998), urban boundary layer (Barlow, 2014), and the urban climate (Zhang et al., 2009), urban roughness (Cao and Lin, 2014) and reduction in sky view factor (Jusuf and Hien, 2009). Farmland and vegetation are characterised with permeable surfaces, low surface roughness length, moderate albedo, high evapotranspiration and moisture availability (Taha, 1997; Grimmond and Oke, 1999a,b), which have been reported to contribute positively in reducing surface thermal conditions of the immediate environment (Rosenfeld et al., 1998; Zhang et al., 2014). On the other hand, typical urban engineered surfaces are often dark materials with low surface albedo, high thermal conductivity, heat storage capacity and impervious surfaces (Taha, 1997; Ashtiani et al., 2014; Yang, 2013). This creates elevated thermal climate with accompanying consequences such as human discomfort (Tomlinson et al., 2011; Emmanuel and Krüger, 2012), increased cost of heating for tropical cities all year round and summer for sub-tropical and middle latitude cities (Priyadarsini et al., 2008; Chow and Roth, 2006), and air quality (Lai and Cheng, 2009).

A recent study of Singapore environment by Li et al. (2013), shows induced effect of urbanisation on UHI formation and alteration of the urban boundary layer. UHI raises major health (Enete et al., 2014) and economic concern (I.S.M. Elsayed, 2012) because of its associated daily elevated temperatures. For instance, the number of deaths linked to heat stroke in Japan has outnumbered other natural causes such as typhoon and tornadoes (Fujibe, 2009). In Japan, ambulances transport more than 10,000 people with heat stroke-related to the hospitals in the Tokyo metropolitan city in summer (Fire and Disaster Management Agency of Japan, 2011). Furthermore, according to a case study in Japan, an increase in the daytime temperature by 1 °C during the summer increases daily maximum energy demand by about 1.9 GW in the Tokyo metropolitan area and its surroundings (Goto et al., 2004).

Many research on urbanisation are channelled towards understanding the influence of urbanisation on the urban climate environment and synoptic processes (Jin et al., 2005), UHI (Rizwan et al., 2008), contributions of urban environments to global warming (Grimmond, 2007a,b), changes of precipitation (Shem and Shepherd, 2009), urban surface run-off (Hamdi et al., 2011), and reduced evapotranspiration and moisture availability in cities (Jiang et al., 2015).

Relative to average global changes, urban areas have experienced more warming (Ren and Zhou, 2014). Ren et al. (2008) carries a detailed analysis of data collected from 282 meteorological stations in Northern China, and discovers that urban warming have impacted prominently on the regional mean annual temperature series in the range of ~0.11 °C per decade. Urban warming has also impacted on the total annual mean surface air temperature change which was estimated to attain ~38% using the national basic reference station dataset. To further validate the influence of urban on global surface temperature, Jones et al. (2008) assessed possible urban influences using sea surface temperature data sets for Eastern Chinese mainland. Their investigation reveals that urban associated warming over China is about 0.1 °C/decade during the period 1951–2004, with true climatic warming accounting for 0.81 °C over this period. Jones et al. (2008) findings agrees roughly with the discovery of Ren et al. (2008) on the contribution of urban warming to global surface temperature. Based on a reanalysis of global weather data from 1950 to 1999, Kalnay and Cai (2003) claims that half of the observed decrease in the diurnal temperature range in the continental United States is due to urban and other land use changes, and estimates 0.27 °C mean surface warming per century to have been due to land-use changes. This estimate is twice as the previous estimates based on urbanisation alone.

Despite the huge number of studies on the impact of urbanisation in other parts of the world, as of the time of reporting this study, only few studies (Sani, 1980, 1993; I. Elsayed, 2012) have been conducted in tropical regions like Malaysia to understand the induced impacts of urbanisation on the regional tropical climate. Most of the studies on urbanisation impact in the region are concerned with economic, social and cultural changes (Agus, 1990; Hill, 1995; Hew, 2003; Yaakob et al., 2010; Gee, 2011; Aziz et al., 2012; Shahbaz et al., 2015). However, there is a growing community on the study of UHI in Malaysia (Shaharuddin et al., 2014; Morris et al., 2015a,b; Rajagopalan et al., 2014; Yusuf et al., 2014; Ahmed et al., 2015; Salleh et al., 2015). Malaysia being a tropical region (Proximity to the equator) is exposed to constant solar radiation exacerbating the UHI effect on its inhabitants. Lack of comprehensive investigation on the evolution and adaption of urban climate (especially UHI) with urbanisation in tropical regions characterised by distinct climatic features relative to other climate zones and thus, non-transferability of research outcomes (Köhler et al., 2002; Roth, 2007) makes this current study imperative to understand tropical urban climate adaption to urbanisation, thermal interaction with the local climate and to bridge the knowledge gap.

Putrajaya, a recently planned and developed federal capital territory from a total farmland is selected to examine the impact of urbanisation growth and its interaction with the local climate over a decade (1999–2011). A planned city with ~85% completion in its development is suitable for climate research, offering the opportunity to formulate urban planning strategies to combat problems posed by urbanisation and its resulting UHI. Apart from the opportunity to combat problems posed by urbanisation, a planned city is a vital source of data on how temperature behaviour varies through the year. This is