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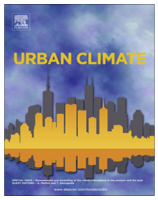

Evaluation of cool roof and vegetations in mitigating urban heat island in a tropical city, Singapore

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A B S T R A C T

A numerical study with a weather research and forecasting (WRF) model at 300-m resolution shows that Singapore's canopy-layer UHI intensity has a strong diurnal cycle, peaking in early morning and keeping almost constant during late night and early morning. The modeled ensemble peak UHI intensity is 2.2 °C and it can reach 2.4 °C during early morning in the intensive industrial region in west Singapore.

Numerical sensitivity tests are carried out to evaluate the mitigation effect of the cool roof and green vegetations at the city scale. The results reveal that the city-scale deployment of cool roofs can greatly reduce the near-surface air temperature and surface skin temperature during the daytime (especially at noon), but has little effect during nighttime. Green vegetation deployment, however, can reduce the near-surface air temperature by more than 1 °C during nighttime when the UHI intensity is high. This reduction can reach 2 °C at 02:00 LT in western Singapore. The detailed analysis shows that the higher latent heat flux and lower heat storage during daytime in green vegetation deployment are the key factors that contribute to the lower sensible heat flux, and hence lower near-surface air temperature. Moreover, the green vegetation will improve human's physiological thermal comfort during early morning. It is therefore suggested that, under the specific meteorological conditions, the green vegetation is preferable in terms of mitigating the (nocturnal) UHI intensity in Singapore, albeit with some uncertainties and caveats to be considered in practice.

1. Introduction

The urban heat island (UHI) effect (a phenomenon that the urban area is hotter than its surrounding rural area) is probably the most pronounced effect of urbanization and human activities in urban areas. The principal factors that generate the UHI are the reduced wind speed due to urban roughness, the trapping of long-wave radiation during nighttime that takes place in the urban canopy, the thermal properties of the building materials, the relative lack of vegetation, and the anthropogenic heat (AH) release due to human activities (Yow, 2007). The UHI is most pronounced on calm, clear nights. Seasonal climatic conditions, daily synoptic conditions, and the diurnal cycle also play key roles in determining UHI characteristics (Arnfield, 2003; Oke, 1982). The UHI phenomenon has profound impacts on the meso- and micro-environment, particularly

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on human thermal comfort and health (Kovats and Hajat, 2008). Here the focus will be on the canopy-layer UHI, which is defined as the near-surface (2-m) air temperature difference between the urban and rural environments.

Numerous studies have been carried out to study the UHI in various climate regions through either observation or numerical modeling (Arnfield, 2003; Yow, 2007). Field measurements and modeling efforts have enlightened the understanding of the characteristics and various factors responsible for UHI development (Chow and Roth, 2006; Ryu and Baik, 2012).

Many modeling studies of the UHI have been performed using numerical weather prediction (NWP) models such as the Pennsylvania State University/National Center for Atmospheric Research mesoscale model (known as MM5, Taha, 1999), the Weather Research and Forecasting (WRF) model (Miao et al., 2009) or the UK Met Office Unified Model (Bohnenstengel et al., 2011). With the development of computational capacity, NWP models can be run at horizontal resolutions of less than 1 km. It is therefore necessary to modify the physics of these models in order to account for the urban effects on evaporation rates, absorption, and reflection of solar radiation, storage of heat, and wind and turbulence fields. The common approach is to use urban canopy models (UCM) embedded within the NWP model. These schemes either model the urban canopy effects of streets and buildings using a single-layer (Kusaka et al., 2001; Kusaka and Kimura, 2004) or multiple-layer parameterization (Martilli et al., 2002).

There are many steps that can reduce the impacts of heat islands (Yow, 2007). These steps include installing cool (high-reflectance) or vegetated roofs, (2) planting trees and vegetation, and (3) switching to cool (high-reflectance) paving materials (Zhou and Shepherd, 2010). With advances in urban modeling, several mitigation strategies for UHI have been proposed and tested with numerical models (see Santamouris, 2014 for a review). Coupling urban schemes within mesoscale models can allow multiple UHI adaptation strategies to be evaluated before deciding on an appropriate course of action (Masson, 2006). The sensitivity tests by Zhou and Shepherd (2010) showed that a doubling of Atlanta's surface vegetation or a tripling of its albedo could effectively reduce the urban surface temperature. Salamanca et al. (2012) studied the UHI pattern over Madrid and tested possible mitigation measures. They showed that a high roof albedo, the use of insulating materials inside the walls, and air conditioning systems that do not directly eject heat into the atmosphere are different strategies that could significantly reduce the UHI (by 1–2 °C) and energy consumption. Observational studies in a tropical city, San Juan, Puerto Rico (Murphy et al., 2011) suggested that tree cover and the shade it provides were successful agents in diminishing daytime warming, whereas park-like green spaces were ineffective in combating warming during the day. Similarly, a study (Papangelis et al., 2012) using WRF in the densely populated Athens, Greece, revealed that an urban park proposed to replace a mainly industrial/commercial area near the city center can induce large cooling (an average greater than 5 °C) over the park's vegetated surfaces during nighttime. However, no significant temperature change over the park was seen during daytime. A recent study by Li et al. (2014) investigated the effectiveness of cool and green roofs as mitigating strategies of UHI using a WRF case study for a heat wave episode. They found that green roofs with relatively abundant soil moisture have an effect in reducing the surface and near-surface UHIs comparable to cool roofs with an albedo value of 0.7.

The majority of the previous studies on the urban environment and urban climate has been in the mid-latitudes. However, much of the predicted urbanization and urban population growth will occur in (sub)tropical regions where UHIs negatively impact virtually all temperature-sensitive aspects of cities throughout the year (Yow, 2007). The observational and numerical studies of a tropical coastal city, San Juan, Puerto Rico (González et al., 2005; Comarazamy et al., 2010; Murphy et al., 2011), have highlighted the importance of urban climatology investigation in tropical regions under the condition of global climate change. Two major differences between the UHI of temperate and tropical cities have been identified (Chow and Roth, 2006): (1) generally the maximum UHI intensity in tropics is lower than in temperate regions; and (2) the time of the maximum UHI intensity (around midnight or near dawn) is later than that in temperate regions. Moreover, previous studies have demonstrated that the driver for UHI development in different climates is different (Zhao et al., 2014), and the effectiveness of UHI mitigation measures is expected to vary from city to city (Li et al., 2014).

In particular, Georgescu et al. (2014) shows that within United States, megapolitan areas located in different climate zones will react to UHI mitigation strategies in diverse ways, signifying he need for geographically appropriate strategies rather than one size fits all solutions. Singapore, as a tropical coastal city state, with a typical equatorial wet climate (see Section 2.1) and high building density, has suffered from UHI and implemented UHI mitigation strategies in the past decade. Therefore, this study serves as an applied research to use the WRF model in Singapore, and will investigate the UHI and its mitigation strategy at the city scale. First the results of a modeling study of Singapore's UHI will be presented. Then the mitigation effects of cool roof and urban vegetation will be discussed. Finally some concluding remarks and discussions will be given.

2. Urban heat island characteristics

2.1. Study area

Singapore is an island state located between 1°09′N to 1°29′N, and 103°36′E to 104°25′E. Its climate is a typical wet equatorial type (Köppen classification: *Af*) with uniformly high monthly mean temperature (26–27.7 °C) and annual rainfall (≈2300 mm) (MSS, 2012). Singapore is located at the southern tip of the Malay Peninsula and is affected by East Asian monsoons. The northeast monsoon season from December to March, which is associated with the highest monthly rainfall and