Urban heat island over northern Taiwan: Numerical study using WRF coupled with a 2-D urban canopy model.

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1. Introduction

The significant interactions between urbanization and the atmospheric environment have become increasingly evident. The important impact of changes in land use and land cover (LULC) on precipitation and climate has also been much emphasized. It is estimated that the world's population will rise to 9.3 billion in 2050 (http://esa.un.org/unpd/wup/index.htm). Furthermore, the most recent report on world urbanization prospects published by the United Nations indicated that in 2014, 54% of the world's population resided in urban areas (http://esa.un.org/unpd/wup/Highlights/WUP2014-Highlights.pdf); and by 2050, the world's urban population is projected to be 66%. Rapid urbanization has resulted in environmental problems including increasing energy consumption and air pollution, deterioration of visibility, significant urban heat island (UHI) effect, urban heavy rainfall, and even local (regional) climate change.

The UHI effect is caused by LULC changes, which bring about variations in physical properties of land, such as albedo, surface roughness, thermal inertia, evapotranspiration efficiency, and in turn alter the climate system. In modeling studies, detailed information of land use and urban parameters are critical for simulation of the UHI effect. To improve the modeling performance in their study on urban boundary layer, Kusaka and Kimura (2004) developed the

Urban Canopy Model (UCM) by implementing urban canopy parameterization in a mesoscale model. In recent years, the Weather Research and Forecasting (WRF) model coupled with the Noah land-surface model and the UCM (WRF-UCM) has been successfully applied to research on the UHI effect in mega-cites of Japan (Kusaka et al. 2012), the United States (Lo et al. 2007), China (Miao et al. 2009), and Taiwan (Lin et al. 2008, 2011). Studies conducted in Taiwan have found that WRF-UCM can improve the simulation of UHI intensity, boundary layer development, land-sea breeze (Lin et al. 2008) and precipitation (Lin et al. 2011). However, the existing UCM (Kusaka and Kimura, 2004) when coupled with the WRF model still has some limitations.

In the original UCM, when the land use in the model grid net is identified as “urban”, the urban fraction value is fixed (Figure 1a). Yet in reality, the categorization of land use and land cover is far more complex; and the existing model is still too rough to reflect the exact land use in urban and non-urban areas. Similarly, the UCM assumes the distribution of anthropogenic heat (AH) to be constant. Such not only may lead to over- or underestimation, the temperature difference between urban and non-urban areas has also been neglected. To overcome the above-mentioned limitations and to improve the performance of the original UCM model, WRF-UCM is modified to consider the 2-D urban fraction and AH. The modified version of UCM (hereafter referred to as WRF-UCM2D) is then employed to assess the impact of urbanization on Taipei city in Taiwan and its simulation performance is compared against that of WRF-UCM. WRF-UCM2D provided more detailed and accurate spatial distribution of areas with urban fraction ranging from 0.01 to 1.0 (Figure 1b). The spatial distribution of AH over the entire studied area ranges from 0 to 50 w/m^2 (Figure 1d) , giving more detailed information at finer resolution. With the improved model, the oversimplified results can be avoided with the percentage of urbanization in the model grid nets more accurately identified according to the actual land use and building density for AH, not only in the city center but also in rural small towns.

2 Preliminary results

To assess the effectiveness of the improved approaches, WRF-UCM2D is applied to the simulation study on impact of urbanization in northern Taiwan. Comparison in simulation performance between the original and improved WRF-UCM is also made. Simulation results show that WRF-UCM2D provides more detailed and accurate spatial distribution of air temperatures, which are sometimes underestimated at urban during daytime by WRF-UCM. The two models have comparable simulation performance for urban areas while large differences in simulated results are observed for non-urban areas, especially at nighttime.

WRF-UCM2D yielded a higher R^2 than WRF-UCM (0.72 vs. 0.48, respectively), while bias and RMSE achieved by WRF-UCM2D were both significantly smaller than those attained by WRF-UCM (0.27 and 1.27 vs. 1.12 and 1.89, respectively). In other words, the improved model not only enhanced correlation but also reduced bias and RMSE for the nighttime data of non-urban areas. The performance of WRF-UCM2D (Figure 2b) is much better than WRF-UCM (Figure 2a) at non-urban stations with low urban fraction during nighttime. It is attributed to energy exchange that enables efficient turbulence mixing in areas with low urban fraction. Energy exchange contributes to reduce air temperatures simulated by WRF-UCM2D, followed by decrease in ground surface temperatures. Moreover, simulation results show that the critical urban fraction is around 0.2, at which the difference in T_{2m} obtained by WRF-UCM2D and WRF-UCM is zero. Finally, the proposed WRF-UCM2D successfully improved the simulation of diurnal variation of air temperature in urban and non-urban areas. The results of this study can be applicable to assessing the impacts of urbanization on air quality and regional climate.

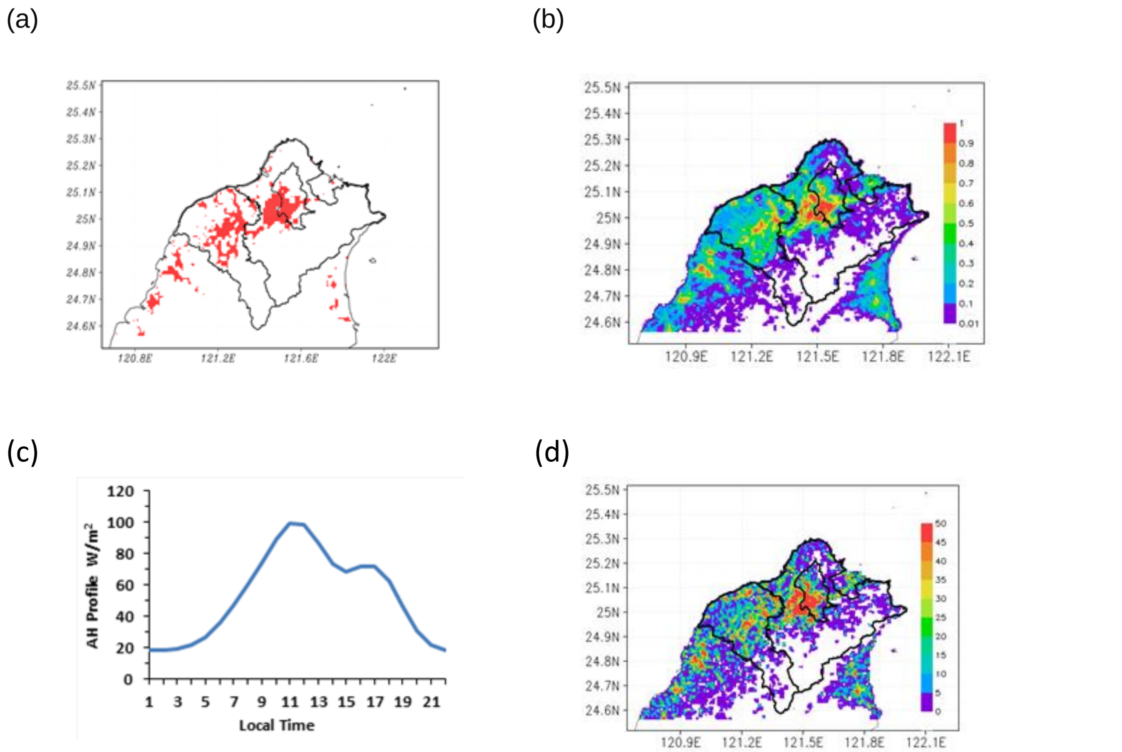
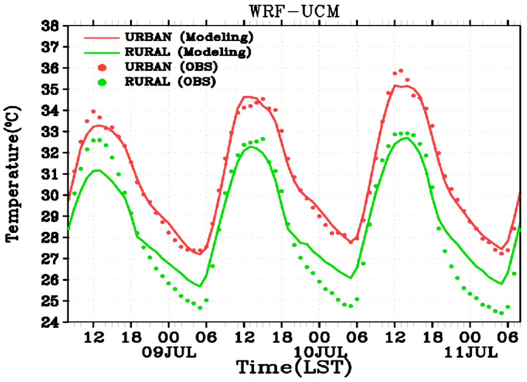


Figure 1 Spatial distribution of urban areas simulated at 1-km resolution (a) by WRF-UCM with urban fraction fixed at 0.7 and (b) by WRF-UCM2D with urban fraction ranging from 0.01 to 1.0. (c) Diurnal variation of AH used in model simulation. (d) Spatial distribution of AH ranging from 0 to 50 w/m² simulated by WRF-UCM2D at 1-km resolution.

(a)



(b)

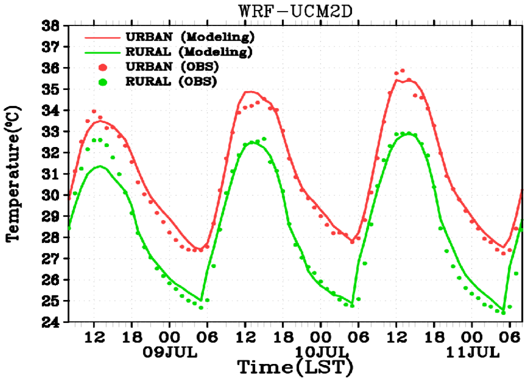


Figure 2. Mean hourly air temperature simulated and observed at 19 urban stations and 21 non-urban stations during the study period by (a) WRF-UCM (b) WRF-UCM2D

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