Urban Heat Island Effect and its Impact on Boundary Layer Development and Precipitation over Northern Taiwan

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Abstract

The impact of the urban heat island (UHI) effect on environmental phenomena and regional climate has been receiving wide attention in recent decades. Taiwan, especially Taipei (located in northern Taiwan, Figure 1), is experiencing a significant urban heat island effect due to its high population density and the uniqueness of the geographic structure. In order to evaluate the impacts of urbanization and UHI effect over northern Taiwan, a next generation mesoscale model, Weather Research and Forecasting (WRF) model coupled with the Noah land surface model (LSM) and Urban canopy model (UCM), was used to study this issue. By using this model, it has significantly improved our simulation results for the prediction of UHI effect, boundary layer development and precipitation over northern Taiwan.

1. INTRODUCTION

Taipei metropolitan (Figure 1) is located in a basin surrounded by high mountains in northern Taiwan. Such a complex geographic structure makes the effect of UHI in Taipei significantly more serious than other cities of similar scale around the world. In this study, the vertical microwave temperature profiler (provided by Taiwan Environment Protection Administration), Lidar, surface meteorological stations, and radio sounding provided by the Central Weather Bureau (CWB) have been used to analyze the study case. The Weather Research and Forecasting (WRF) model coupled with the Noah land surface model and Urban Canopy model (WRF-Noah-UCM) (Tewari et al. 2006) was employed to evaluate the impact of the UHI effect on the development of the boundary layer, and land–sea breeze circulation in northern Taiwan. This WRF-Noah-UCM coupled model includes detailed parameters of sensible and latent heat flux, soil heat flux and anthropogenic materials which provide more realism to evaluate the impact of the UHI effect in northern Taiwan.

2 Model configuration and Land use in Taiwan

In this study, the Yonsei University (YSU) (Hong and Dudhia 2003) planet boundary layer scheme was adopted. The YSU scheme is a modification of the MRF (Medium-Range Forecast) scheme to include explicit entrainment fluxes of heat, moisture and momentum, counter-gradient transport of momentum, and different specifications of the boundary layer height (BLH). The anthropogenic heat is assumed by 200 W/m² (estimation method described in Lin et al. 2008) in the control study. The initial and boundary conditions for WRF were obtained from NCEP-FNL data sets at 6-hour intervals. Four nest domains were constructed with spatial grid resolutions of 27, 9, 3, and 1 km which contained 150×122, 100×88, 100×160 and 91×79 grid boxes, respectively, from west to east and south to north. In the following discussion, we only show the finest domain (1 km resolution) to compare with the observation. For the urban type in the UCM model, the high intensity residence is employed in the model to represent the high population density in the Taipei area. In this study, we set the model run from 12UTC (2000LST) 16 June, 2006 and the total running period for 36 h for each experiment.

Figure 2a shows the original USGS 25-category land use (LU) data and land Coverage (LC) data linked with the WRF meteorological modeling system which is roughly a 1-km resolution data element, but somewhat outdated compared to the satellite image shown in Figure 1b. Apparently, most of the western plain is classified as dry crop land use and the urban size is far from the real current urban size in the original USGS land use dataset (Figure 2a). With this in mind, we have replaced the original USGS 25-category data over Taiwan with the MODIS satellite LU 1 km resolution data (Figure 2b). Based on this improvement, we could take our effort one step further by using the WRF-Noah-UCM coupled model to study the urban heat island effect over northern Taiwan.

3. Result

Figures 3a-b show the comparison of the surface temperature between observation and model prediction during the daytime, nighttime, and in the morning (not shown). In Taipei city, there are more than 10 surface air temperature monitoring stations and enable us to the comparison. The numbers in Figure 3a-b represent the observed air temperature in northern Taiwan and the shaded areas are model prediction. The colors of the numbers in the figure are same as those of the simulation temperature scale. In other words, if the predictions of
The significant highest temperature is observed in the city center during the daytime. Obviously, the air temperature in the city center is about 1–2°C higher than that of the simulation. However, during the nighttime and in the early morning the differences in air temperature are less then 1°C at most of the stations. Figure 3c shows the time series of the vertical temperature profile (measured by MTP-HE system) in Taipei from 00:00 LST 17 June–08:00 LST 18 June, 2006. During the nighttime and in the earlier morning the difference was less then 1°C. Although, our simulation underestimated during the daytime, it is important to note that our WRF-Noah-UCM coupled model can predict the UHI effect reasonably well, especially during the nighttime and early morning.

Sensitivity tests indicated that anthropogenic heat (AH) play important roles for PBL development and UHI intensity in the Taipei area, especially during night time and early morning. On average, when we increased 100 W/m² of AH in the model, the average surface temperature could increase nearly 0.3°C in Taipei. In addition, the UHI effect also has a significant impact on land-sea circulation (not shown). The control run had a stronger sea-breeze than both caseAH0 (anthropogenic heat =0) and case USGS (land use= USGS) due to the enhanced sensible heat flux. On the contrary, the land breeze for the control run is less than these two cases during the night time. These phenomena are adverse to air pollution diffusion and have a significant impact on the air quality during night time.

To evaluate the urbanization impact on precipitation, a thunderstorm case occurred on July 17, 2006 was examined by this WRF-Noah-UCM model. Comparing with the radar reflectivity and rainfall stations observed by Center Weather Bureau, the model predicted reasonably well for the accumulation rainfall distribution (Figure 4) on the episode day. Numerical study suggests that the heat-island effect could perturb thermal and dynamic processes and hence affect the location of thunderstorms and precipitation over northern Taiwan.

References:
Figure 2. (a) The original land use in the model provided by USGS (b) MODIS land use in 2005.

Figure 3. The observation (denoted by number) by stations and simulation (shaded) 10 m air temperature at (a) 14 LST 17 June, 2006 (b) 20 LST 17 June, 2006 (c) The time series of vertical air temperature monitored by microwave temperature profiler in Taipei (shaded) and simulation result (contour lines) from 0000LST 17 June to 0800LST 18 June, 2006.
Figure 4  Rainfall distribution on 17 July, 2006 for  
(a) observation  (b) Simulation result with MODIS land use (c)  
Simulation result with USGS land use