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Response of urban heat island to future urban expansion over the Beijing–Tianjin–Hebei metropolitan area

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A B S T R A C T

Urban expansion plays a dominant role in the urban heat island (UHI) formation and is thus the essence and fundamental characteristic of the urban fabric. In this study, the responses of UHI to the urban expansion in the past decades were simulated using the coupled weather research forecast/urban canopy model (WRF/UCM) system from the 1980s to 2005 and in the future in 2050 embedded with the fine spatial resolution land use/land cover (LULC) datasets over the Beijing–Tianjin–Hebei (BTH) metropolitan area. With the urban expansion, the validations suggested that the designed models in this research can well simulate the generation and development of UHI. Due to urban expansion, the minimum temperature would rise by about 5 K in the newly developed areas. The temperature over the old urban areas would also increase (<1 K) because of the surrounding newly developed urban areas. The footprint of urban growth, in particular the minimum temperature, was clearly captured in the three scenarios by almost all the variables. These results were quite interesting, and it indicated a more uncomfortable urban environment in the future, especially at night, when the temperature changes are larger due to urban expansion.

1. Introduction

There has been a surge of urban expansion in China, with urban areas increasing by over 20% from 1980 to 2005 (Liu & Tian, 2010). In view of high economic growth and population density in China, there is an upward trend seen in urbanization. Urban climate phenomenon (UHI) has been the result of the urbanization process accompanied by the conversion from rural to urban. Statistical models, in particular correlation and regression, have been employed widely to determine the effect of urbanization on surface UHI (SUHI). Land surface temperature (LST) derived from thermal infrared (TIR) remote sensing images correlated with LULC change, built-up areas, and vegetation in cities (Bounoua, Safia, Masek, Peters-Lidard, & Imhoff, 2009; Chen, Zhao, Li, & Yin, 2006; Connors, Galletti, & Chow, 2013; Guo, Wang, Cheng, & Shu, 2012; He, Liu, Zhuang, Zhang, & Liu, 2007; Weng, Lu, & Schubring, 2004, 2006; Zhang et al., 2013). Although statistical models are useful to describe the patterns and explore the associated factors of the UHI, they cannot reveal the generation and development of UHI (Voogt & Oke, 2003). In addition, remote sensing images measure only the surface skin temperature, while the near-surface air temperature correlates more to human comfort. Although these two types of temperatures are closely related, they are actually different (Gallo, Hale, Tarpley, & Yu, 2011). A series of sensitivity experiments are necessary to get a deeper insight into the UHI and the effects of urban expansion on UHI from a modeling perspective.

Recently, the weather research forecast (WRF) numerical

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modeling system (Skamarock et al., 2005) has attracted much attention. This meso-scale numerical modeling system is designed for atmospheric research and operational forecasting. Some large cities and urban agglomerations, such as Tokyo (Kusaka & Kimura, 2004), Taipei (Lin et al., 2008; Lin, Chen, Chang, & Sheng, 2010), Nanjing (Yang, Zhang, & Qian, 2012), and Beijing (Miao et al., 2009; Zhang et al., 2009), as well as Yangtze River Delta (Zhang, Gao, Wang, & Chen, 2010), the BTH metropolitan area (Wang, Yan, Liu, & Zhang, 2013, Wang, Zhang, & Yan, 2013), and Pearl River Delta (Cheng & Chan, 2012; Wang, Wu, & Liang, 2009), have witnessed the simulation of the variation in UHI using this modeling system. The capability of the WRF modeling system has been highlighted to explore the impact of LULC change on UHI at the local or regional scales. However, when simulating the effect of urban expansion on UHI (Wang, Feng, Yan, Hu, & Jia, 2012), most studies focused only on the ideal experiments (e.g., replacing urban areas by cropland), which is insufficient to characterize the real urbanization process. The default LULC data from the United States Geological Survey (USGS) or Moderate Resolution Imaging Spectroradiometer (MODIS) products in the WRF modeling system may lead to bias because of its coarse spatial resolution (Lin et al., 2010). To simulate the effect of urban expansion on the UHI over the BTH metropolitan area, in this study, the coupled WRF/UCM modeling system embedded with three periods of fine spatial resolution LULC data were used. Part of this study included scenarios of future urbanization simulated using LULC predicted by a land conversion model (Huang, Zhang, & Wu, 2009).

2. Study area and data

2.1. Study area

The BTH metropolitan area is situated in the North China Plain. Since being branded as an economic center of northern China, this area has undergone dramatic economic growth and massive urbanization from the time of the reform process in late 1978. The total residential population over this region has doubled from 1984 to 2008 (China City Statistical Yearbook, 2009). Likewise, the built-up area expanded to a large extent taking up areas which were previously agricultural zones. This study takes the metropolis area as the study area, including Beijing, Tianjin, and most parts of Hebei province, which is indicated by the inner rectangle in Fig. 1. The two red rectangles represent the two domains in WRF model design, which is explained in Section 3.

2.2. Data

2.2.1. Land use and land cover data

LULC datasets in the 1980s and 2005 covering the BTH metropolis area were obtained from "*Data Sharing Infrastructure of Earth System Science, the Chinese Academy of Sciences* (*DSIESS,CAS*)" (http://www.geodata.cn/Portal/metadata/viewMetadata.jsp?id=100101-11860). They have a high accuracy of 80–90% when compared to extensive field surveys (*DSIESS, CAS*). These datasets have a fine spatial resolution (100 m by l00 m) and are suitable for characterizing urban growth between the 1980s and 2005.

To embed the fine spatial resolution LULC data into the WRF modeling system, they were resampled to dimensions of 1 × 1 km using the "majority" resampling technique. They were then reclassified according to the default USGS-24 categories and re-projected to WGS-84. The final LULC maps are shown in Fig. 2a, b. The LULC in 2050 (Fig. 2c) was predicted using the statistical land conversion model by Huang et al. (2009), which is introduced in Section 3.1. The three periods of LULC data in the 1980s, 2005, and 2050 were used to characterize the real urbanization process in the past decades and the future possible pattern of urbanization. All of them were finally embedded into the coupled WRF/UCM modeling system.

2.2.2. Reanalysis data

Reanalysis data used in this research were obtained from the "*National Centers for Environmental Prediction*/Global Forecast System *(NCEP/GFS)*" (http://www.nco.ncep.noaa.gov/pmb/products/gfs/). The datasets provide both the initial and the boundary conditions on 1° by 1° grids at every 6 h continuously (including 00:00, 06:00, 12:00, 18:00) for the WRF simulation.

2.2.3. Meteorological data

To validate the accuracy of the designed model in this study, the air temperature data were obtained from the "*China Meteorological Data Sharing System*" (http://cdc.cma.gov.cn/home.do). Nineteen meteorological stations distributed in the study areas were used, which are listed in Section 3.

3. Methodology

3.1. Statistical land conversion model

In this study, a statistical land conversion model developed by Huang et al. (2009) was used to simulate urban–rural LULC conversion. This model was proposed by establishing the logistical regression relationship between the land change (e.g., zero was considered as "no change", 1 was considered as "change") and the explanatory factors. In this study, the urban–rural conversion in the year 2050 was forecasted. To produce the dependent urban–rural map in the 1980s and 2005, the urban built-up areas were reclassified as the "urban" category, the seas and deserts were reclassified as "others", and all the other types were reclassified as the "rural" category. Five explanatory factors, including percentage of urban area, Euclidian distance to urban area, Euclidian distance to roads, population density, and slope, were employed to predict land conversion from rural to urban areas. The datasets, which were used to derive the explanatory factors, were obtained from the DSIESS, CAS, including road, population density, and digital elevation data.

3.2. WRF/UCM simulation

3.2.1. Parameterization schemes

The UCM, together with the newest 3.5.1 version of the WRF modeling system, was employed in this study. With the spatial resolution adjusted at 20 km for the outer domain and 4 km for the inner domain, respectively, two levels in a nested grid were used (Fig. 1). The inner nested urban domain, D02, was centered over the BTH metropolitan area. The outer domain, D01, covering most of northern China, presented the boundary conditions for the inner domain. The geophysical coordinate system adopted in this study was the Lambert projection.

In the case of the input parameters required by the WRF modeling system, the initial boundary conditions were supplied by the NCEP/GFS 6-hourly reanalysis data (see Section 2.2.2, *Reanalysis data*). The terrestrial, geographical input data had a spatial resolution of 30". The default USGS LULC data were replaced by the fine spatial resolution LULC data (see Section 2.2.1, *Land use and land cover data*). The main physical parameterization schemes adopted in this study are shown in Table 1.

The simple single-layer UCM was used to take the geometry of urban areas into account in the wind shear and surface energy budget calculations (Chen et al., 2004, 2011; Kusaka, Kondo, Kikegawa, & Kimura, 2001). As it is difficult to obtain the detailed