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A modeling study on the effect of urban land surface forcing to regional meteorology and air quality over South China

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HIGHLIGHTS

- Land surface forcing to meteorology and air quality in South China is studied.
- Urban land-use changes increase T_2, PHLH and rainfall, but decrease WS_{10} and RH_2.
- Urban land-use changes increase O_3 but decrease PM_{10} at surface.
- The effect of urban land-use changes is significant in big cities.

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ABSTRACT

The change of land-use from natural to artificial surface induced by urban expansion can deeply impact the city environment. In this paper, the model WRF/Chem is applied to explore the effect of this change on regional meteorology and air quality over South China, where people have witnessed a rapid rate of urbanization. Two sets of urban maps are adopted to stand for the pre-urbanization and the present urban land-use distributions. Month-long simulations are conducted for January and July, 2014. The results show that urban expansion can obviously change the weather conditions around the big cities of South China. Especially in the Pearl River Delta region (PRD), the urban land-use change can increase the sensible heat flux by 40 W/m^2 in January and 80 W/m^2 in July, while decrease the latent heat flux about −50 W/m^2 in January and −120 W/m^2 in July. In the consequent, 2-m air temperature (T_2) increases as much as 1 °C and 2 °C (respective to January and July), planetary boundary layer height (PBLH) rises up by 100–150 m and 300 m, 10-m wind speed (WS_{10}) decreases by −1.2 m/s and −0.3 m/s, and 2-m specific humidity is reduced by −0.8 g/kg and −1.5 g/kg. Also, the precipitation in July can be increased as much as 120 mm, with more heavy rains and rainstorms. These variations of meteorological factors can significantly impact the spatial and vertical distribution of air pollutants as well. In PRD, the enhanced updraft can reduce the surface concentrations of PM_{10} by −40 μg/m^3 (30%) in January and −80 μg/m^3 (50%) in July, but produce a correlating increase in the concentrations at higher atmospheric layers. However, according to the increase in T_2 and the decrease in surface NO, the surface concentrations of O_3 in PRD can increase by 2–6 ppb in January and 8–12 ppb in July. Meanwhile, there is a significant increase in the O_3 concentrations at upper layers above PRD, which should be attributed to the increase in air temperature and the enhanced upward transport of O_3 and its precursors. As for some relative small cities, such as Haikou, there is very little variation in surface PM_{10} and O_3 in both months, implying less urbanization in these areas. Moreover, the depletion of O_3 by NO may be the main cause of the reduction of O_3 at upper layers in these small cities.

1. Introduction

Urbanization and its impacts on regional meteorology and air quality have been widely acknowledged, observed, and

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investigated (Mirzaei and Haghighat, 2010). Previous studies have illustrated that urbanization can affect air quality in many ways, which are mainly associated with the increase of air pollutant emissions, the release of anthropogenic heat, and the change of land covers (Xie et al., 2016b). With the increase of urban expansion induced by human activities, more land surfaces have been turned from the natural to the artificial ones, which can lead to the great changes in such properties of the earth surface as roughness, thermal capacity, albedo and vegetation coverage. These changes can result in the subsequent changes in local circulations and weather conditions, and thereby may have further effect on transport and diffusion of air pollutants. Consequently, the impacts of urban land-use change on regional meteorology and air quality have become the hot topics of environmental sciences (Wang et al., 2007, 2009; Zhang et al., 2008, 2010; Miao et al., 2009; Chen et al., 2014; Zhu et al., 2015; Li et al., 2016).

In previous studies on the effect of urban land surface forcing, most researchers usually just emphasized its impact on local climatic characteristics. Some have discussed the effects on the advent and development of the urban heat island (Roth, 2000; Montavez et al., 2008; Zhang et al., 2008; Wang et al., 2009; Meng et al., 2011). Some have investigated the effects on the changes in local circulation and precipitation (Bornstein and Lin, 2000; Kaufmann et al., 2007; Lo et al., 2007; Lin et al., 2008; Shem and Shepherd, 2009; Lu et al., 2010; Zhang et al., 2010; Wu et al., 2011; Feng et al., 2012; Wang et al., 2014). Meanwhile, with the development of urban canopy models, numerical models have been widely applied in recent researches. For instance, Lemonsu and Masson (2002) developed and applied the Meso-NH model to simulate the changes of urban heat islands in Paris and the collateral effects on land and sea air currents. Kusaka et al. (2001), Kusaka and Kimura (2004) and Miao et al. (2009) used the WRF model with a single layer urban canopy model (SLUCM) to model heat islands in megacities, and study their effects on the characteristics of boundary layers. Nowadays, some of these urban canopy parameterization schemes have been incorporated in WRF/Chem, which can help us to precisely simulate the complicated flow fields in urban areas (Chen et al., 2011; Meng et al., 2011; Feng et al., 2012; Kang et al., 2014; Li et al., 2014; Xie et al., 2016a, 2016b).

In addition, several previous studies also have tried to figure out the effect of urban land surface forcing on air quality (Civerolo et al., 2007; Cheng et al., 2008; Wang et al., 2007, 2009; Zhang et al., 2008, 2010; Miao et al., 2009; Chen et al., 2014; Liao et al., 2014, 2015; Zhu et al., 2015; Li et al., 2016). With aid of WRF-CMAQ and high resolution topographic, Cheng et al. (2008) simulated the effect of land-use changes on weather condition and air quality in Houston-Galveston of USA, and pointed out that the simulation of boundary layer and air quality can be improved by using high-precision land-use data. Civerolo et al. (2007) studied the effect of projected future urbanization on the air quality of New York City under IPCC A2 climate scenario, and found a significant increase in O_3 concentrations. Zhu et al. (2015) simulated and discussed the impact of Shanghai urban land surface forcing on O_3 chemistry in the downstream city. By using the WRF/Chem model, Liao et al. (2015) investigated the effects of urban expansion on air quality over the Yangtze River delta in China, and indicated that urban land-use changes can cause the decrease of surface PM_{10} and the increase of surface O_3 both in cold and hot seasons. Li et al. (2016) also studied the similar issue in the Pearl River Delta region (PRD) of China, but only focused on O_3 formation. All the above studies have proved that the changes in local climate and boundary layers induced by urban land-use change can further result in varying in the transport and the diffusion of air pollutants, and thereby greatly influence the regional air quality.

South China is one of the most economically vibrant and densely populated areas in the world. Over the past decades, many areas in South China have experienced the accelerated urbanization process. Urbanization has brought about significant change to the properties of ground surfaces, and consequently increasing problems of urban heat islands and air pollution in these areas. So, many previous researches have quantified the effects of urbanization on urban climate and air quality in South China (Lo et al., 2007; Wang et al., 2007, 2009; 2014; Lin et al., 2009; Lu et al., 2010; Meng et al., 2011; Wu et al., 2011; Feng et al., 2012; Chen et al., 2014; Li et al., 2014, 2016). Most of these investigations merely studied how urban land-use changes impact the meteorological conditions (Lo et al., 2007; Lin et al., 2009; Lu et al., 2010; Meng et al., 2011; Wu et al., 2011; Feng et al., 2012; Li et al., 2014). Only a few have linked the changes in meteorology with the regional air quality (Wang et al., 2007, 2009; Chen et al., 2014; Li et al., 2016). However, among these limited studies, researchers usually paid attention to one species like SO_2 (Chen et al., 2014) or O_3 (Wang et al., 2007, 2009; Li et al., 2016), and the reported results were just based on the simulation for one pollution episode (Wang et al., 2007; Chen et al., 2014) or one typical month (Wang et al., 2009; Li et al., 2016). So, simulation analyses for more chemical species in different seasons should be performed to promote our understanding.

To fill the knowledge gap, we apply the WRF/Chem model coupled with SLUCM to simulate the effects of urban land-use change on regional weather conditions and air quality over South China in different seasons. Two sets of urban maps are adopted to represent the pre-urbanization (early 1990s) and the present urban land-use distributions. Month-long simulations are conducted under the climate conditions of January and July 2014 to represent different seasons. In this paper, detailed descriptions about WRF/Chem with special configurations are presented in Sect. 2. Main results are given in Sect. 3, including model validation as well as the three-dimensional changes of meteorological factors and air pollutants. In the end, a summary is shown in Sect. 4.

2. Methodology and data

2.1. Air quality model and its configuration

WRF/Chem version 3.5 is applied to study the impact of urban land surface forcing on weather conditions and air quality over South China. WRF/Chem is a new generation of air quality model, which is developed by the National Center for Atmospheric Research (NCAR) of USA. Its meteorological (WRF) and chemical (Chem) components are fully coupled, and share the same coordinates and physical parameterizations. The feedbacks between meteorology factors and air pollutants are also included in WRF/Chem. Many previous simulations have demonstrated that WRF/Chem is a reliable tool for simulating air quality from city-scale to meso-scale in China (Jiang et al., 2008; Wang et al., 2009; Liu et al., 2013; Liao et al., 2014, 2015; Li et al., 2016; Xie et al., 2016a).

In this study, two nested domains are used. As shown in Fig. 1, the outermost domain (Domain 1) contains mostly Chinese territory and part of Southeast Asia below 35°N, while the innermost domain (Domain 2) covers the areas between 101.7–119°E and 16.5–25.3°N including South China. The horizontal grids of two domains are 121×95 and 192×105, with the grid spacing of 27 km and 9 km, respectively. In previous studies on how the urban land-use change impact regional meteorology and air quality, many researchers have proved that the 9-km grid is sufficient and the modeling results are acceptable (Wang et al., 2009; Yu et al., 2014; Liao et al., 2014, 2015; Xie et al., 2016a). To balance the precision and the time consumption, the resolution of the finest domain is chosen to be 9 km. For all domains, from the surface layer to the top