Urban Modification in a Mesoscale Model and the Effects on the Local Circulation in the Pearl River Delta Region

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ABSTRACT

The Pearl River Delta (PRD) region, located in the southern part of Guangdong Province in China, is one of the most rapidly developing regions in the world. The evolution of local and regional sea-breeze circulation (SBC) is believed to be responsible for forming meteorological conditions for high air-pollution episodes in the PRD. To understand better the impacts of urbanization and its associated urban heat island (UHI) on the local- and regional-scale atmospheric circulations over PRD, a number of high-resolution numerical experiments, with different approaches to treat the land surface and urban processes, have been conducted using the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5). The results show that an accurate urban land-use dataset and a proper urban land-use parameterization are critical for the mesoscale model to capture the major features of the observed UHI effect and land–sea-breeze circulations in the PRD. Stronger UHI in the PRD increases the differential temperature gradient between urbanized areas and nearby ocean surface and hence enhances the mesoscale SBC. The SBC front consequently penetrates farther inland to overcome the prevailing easterly flow in the western part of inland Hong Kong. Additional sensitivity studies indicate that further industrial development and urbanization will strengthen the daytime SBC as well as increase the air temperature in the lowest 2 km of the atmosphere.

1. Introduction

It has been known for some time that urban cities are warmer than their rural surroundings. In cities, where there is less evaporative cooling, buildings and artificial surfaces are typically more capable of storing solar energy than natural surfaces are. In addition, human and industrial activities produce extra heat to the ambient environment, causing higher near-surface temperature in a city. This phenomenon is called the urban heat island (UHI) effect. It has been observed since the 1960s (Woolum 1964; Bornstein 1968), and air temperature in a city can be 1°–4°C higher than the surrounding countryside (World Meteorological Organization 1984). In the past 30 years, a number of climatological and observational studies have recognized that the UHI can have a significant influence on local-scale and mesoscale weather as well as microclimate. Early climatological studies (Khemani and Murty 1973; Changnon et
The Pearl River Delta (PRD), located in the southern part of Guangdong Province in China, is a region of 41,700 km² in size and 50 million in population. Major cities in the region include Hong Kong, Guangzhou, Shenzhen, Dongguan, Zhongshan, Foshan, and Macau (see Fig. 1a). As a result of the economic reform started at the end of the 1970s in China, the economic and industrial growth in the PRD has been phenomenal. The region is now one of the world’s largest manufacturing and industrial bases. However, the rapid urbanization has been causing several environmental impacts in the region, such as climate change and substantial air-quality deterioration.

According to Hong Kong Observatory (HKO), the UHI effect accounts for a difference of 8°C or above in the daily minimum temperatures between urban and rural areas in Hong Kong during winter (Leung and Ng 1997). The urban development is also related to a reduction of visibility, an increase in cloud amount, and a decrease of solar radiation. The number of heavy-rain days has also increased during the period of 1947–2002 in Hong Kong (Leung et al. 2004). From the annual report by the Hong Kong Environment Department (HKEPD; HKEPD 2003), the percentage of time of having poor visibility and the number of ozone episode days have been showing an increasing trend in recent years. The number of days with poor visibility had also increased in the major PRD cities such as Guangzhou and Shenzhen (Ch2M Hill (China) Limited 2002). These indicate the deteriorating air quality in Hong Kong and the entire PRD region.

Because most of the urban areas are located near the coast in the PRD, with calm winds or weak synoptic forcing where most severe air-pollution episodes occurred, sea-breeze circulation (SBC) as well as HIC can occur at the PRD. The SBC has been known to be a significant influence on airflow pattern and to affect the air quality over Hong Kong (Kok et al. 1997; Huang et al. 2005; Fung et al. 2005; Lo et al. 2006). On 1–3 November 2003, a record-high air-pollution episode occurred in Hong Kong and PRD. The air-pollution index¹ (API) had topped 200, and the HKEPD issued the first severe-air-pollution warning since air-quality monitoring was introduced in 1995. One of the main reasons causing this pollution episode, as given by Wu et al. (2005), is a long-period accumulation of pollutants in PRD by land–sea-breeze circulation before the event.

However, because of limited monitoring stations and observations, the SBC and HIC structures in PRD are still not well understood. To manage better the rapidly deteriorating air quality, a better understanding of the local and regional circulation, including the complex interactions between the local SBC and the urban environment in the PRD, is needed. It is generally agreed that the land surface process has substantial influence on both large-scale and mesoscale circulation (Chen and Dudhia 2001). An accurate description of land surface fluxes is important for capturing the evolution of the diurnal planetary boundary layer (PBL), a parameter of primary importance for air-quality studies. An air-quality model cannot perform well without good meteorological condition input from a meteorological model, whereas a finescale meteorological model cannot perform well without a good parameterization of urban land use. Hence, in this study we used a mesoscale model coupled to different approaches of treating urban land use to investigate the formation of meteorological conditions conducive to the 1–3 November 2003 high-air-pollution episode.

This study investigated the impacts of rapid urbanization in the PRD on the local- and regional-scale circulations. In the first part, we used a nonhydrostatic, three-dimensional mesoscale meteorological model [the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5)] to understand and evaluate three different approaches to treat the UHI and their effects on SBC structures over Hong Kong and the PRD region. The first MM5 experiment used the default MM5 surface characteristics with a simple land surface model (LSM; MM5-slab) (Dudhia 1996). The second experiment was carried out by replacing the standard MM5 land use with an up-to-date PRD land-use dataset. The third experiment further enhanced the second experiment with an advanced land surface model [the National Centers for Environmental Prediction (NCEP)–Oregon State University–U.S. Air Force–National Weather Service Office of Hydrologic Development (Noah) LSM] (Chen and Dudhia 2001) with a bulk urban land-use treatment. After the evaluation of model performances, sensitivity experiments were conducted for various urban coverage extensions to understand the potential effects of

¹ The API is a simple way of describing air-pollution levels in Hong Kong. It converts air-pollution data from several types of pollutants into a value ranging from 0 to 500. An API number of 200 indicates a very high air-pollution level.
rapid urban growth on the local wind and temperature structures in the PRD. We present in section 2 the numerical models and data used in this study. Section 3 summarizes the results from numerical simulations using three different urban land-use treatments and their evaluation. In section 4, numerical experiments using different scenarios of urban extension are explored.
2. Numerical models and land-use distribution in the PRD

a. Meteorological model and configuration

The meteorological model used in this study is MM5, version 3.6.3. It is a limited-area, nonhydrostatic, primitive equation model with terrain-following sigma coordinates (Dudhia 1993; Grell et al. 1994). It has been a widely used community model designed to predict mesoscale and regional-scale atmospheric circulations. Previous studies also proved that MM5 has good performances in numerical weather prediction, air-quality studies, and hydrological studies over different parts of the world (Warner et al. 1991; Mass and Kuo 1998; Vaughan et al. 2004).

Figure 2 shows the model domains. Four nested domains with horizontal grid spacings of 40.5 (D1; mesh size of 233 × 188), 13.5 (D2; mesh size of 133 × 148), 4.5 (D3; mesh size of 100 × 91) and 1.5 (D4; mesh size of 151 × 136) km were used. Two-way nesting was used such that meteorological variables in an inner domain could be fed back to the coarse domain, and vice versa, through the nested boundary (Zhang et al. 1986). The Lambert conical conformal map projection was used as the model horizontal coordinates, with true latitudes at 30° and 60°N. The outermost 40.5-km domain covers all of China and is designed to capture the synoptic-scale features, whereas the innermost 1.5-km domain covers Hong Kong and PRD and is designed to resolve local-scale circulation features. The verifications and detailed
The simple explicit microphysical parameterization for cloud water, rainwater, and ice was applied in all domains (Dudhia 1993). The Grell convective parameterization scheme was used in D1 and D2 (Grell 1993), and explicit convection was used in D3 and D4. Shortwave radiation processes were handled using a cloud radiation scheme (Grell et al. 1994) and the Rapid Radiative Transfer Model (Mlawer et al. 1997) was applied for longwave radiation processes. The NCEP Medium-Range Forecast (MRF) scheme was applied for the PBL scheme (Hong and Pan 1996).

The MM5 runs were initialized using the $1^\circ \times 1^\circ$ NCEP Final Analysis (FNL) data as first-guess fields. The lateral boundary conditions of the outermost domain were obtained by linearly interpolating 6-hourly FNL data. The first-guess fields on the MM5 grid were improved by incorporating upper-air and surface observations available on the Global Telecommunication System using the Cressman (1959) objective-analysis scheme. In addition, the upper radiation boundary condition of Klemp and Durran (1983) was used to reduce energy reflection from the model top, preventing noise and energy from being blown up vertically. The sea surface temperature was held constant during the simulations (Reynolds and Smith 1994).

b. Land surface model and parameterization of urban land use

The LSM used in MM5 was originally developed at the Oregon State University (OSU) in the mid-1980s (Pan and Mahrt 1987) and has been widely tested and evaluated (e.g., Chen et al. 1996, 1997; Berbery et al. 1996, 1999; Betts et al. 1997; Yucel et al. 1998; Hinkelmann et al. 1999; Angevine and Mitchell 2001; Berbery 2001; Marshall et al. 2003). The OSU LSM and its successor, the Noah LSM, have been implemented as the land model component in the NCEP operational eta Model (Chen et al. 1997; Ek et al. 2003) and the state-of-the-art research model MM5 (Chen and Dudhia 2001). The Noah LSM consisted of the diurnally dependent Penman potential evaporation approach of Mahrt and Ek (1984), the multilayer soil model of Mahrt and Pan (1984), and the primitive canopy model of Pan and Mahrt (1987). Later improvements include the bare-soil evaporation approach of Noilhan and Planton (1989), the canopy-resistance formulation used by Jacquemin and Noilhan (1990), and the surface runoff scheme of Schaake et al. (1996). The Noah LSM has one canopy layer and four soil layers. The soil-layer thicknesses are 0.1, 0.3, 0.6, and 1.0 m from the ground surface to the bottom, with a total soil depth of 2 m. MM5 simulations of surface radiation, precipitation, and near-surface winds, humidity, and temperature provide the external forcing for the Noah LSM. The Noah LSM then provides surface sensible heat flux, latent heat flux, and skin temperature as lower boundary conditions to MM5. These heat and moisture fluxes are then used to drive the atmospheric boundary layer.

The Noah LSM has recently been enhanced with a simple parameterization for urban land use (Liu et al. 2006). It includes 1) increasing the roughness length from 0.5 to 0.8 m to represent turbulence generated by roughness elements and drag from buildings, 2) reducing surface albedo from 0.18 to 0.15 to represent the shortwave radiation trapping in the urban canyons, 3) using a larger volumetric heat capacity of $3.0 \times 10^6$ J m$^{-3}$ K$^{-1}$ for the urban surface (walls, roofs, and roads), which usually consists of concrete or asphalt materials, 4) increasing the value of soil thermal conductivity to 3.24 W m$^{-1}$ K$^{-1}$ to parameterize large heat storage in the urban surface and underlying surfaces, and 5) reducing the green vegetation fraction and soil moisture over the urban city to decrease evaporation. These urban land-use enhancements appear to have significant improvements for representing urban physical processes over Oklahoma City, Oklahoma (Liu et al. 2006).

c. The two land-use datasets

In the coupled MM5–Noah modeling system, vegetation/land use is one of the primary variables that control the land surface processes and the PBL structure, because various physical parameters of surface characteristics, such as albedo, emissivity, roughness length, and thermal inertia are determined by the land-use category. In standard MM5, typical land-use classification is given by a 30-s-resolution U.S. Geological Survey (USGS) global land cover characteristics database with 24 vegetation categories. This land-use dataset is derived from 1-km Advanced Very High Resolution Radiometer (AVHRR) data in a 12-month period spanning from April 1992 to March 1993.
Fig. 3. Land-use map of the innermost 1.5-km D4 given by (a) original USGS, and (b) new 2003 HKPD land use. The gray shades indicate urban, cropland, grassland, forest, water, and other according to the figure legend.
The USGS land-use distribution in the 1.5-km D4 is shown in Fig. 3a. For simplicity, the 24-category USGS vegetation categories with similar properties are regrouped into five major classifications: urban, cropland, grassland, forest, water body, and other. In the USGS land-use map (Fig. 3a), the majority of the PRD area is still an agricultural region; 45.6% of the domain mass is cropland while urban areas only contribute 0.5% (Table 1). Most major cities in the PRD such as Shenzhen, Dongguan, Guangzhou, and Zhuhai (see Fig. 1a for the locations) had not been highly urbanized, and some of them were typical small rural towns. The Chinese economy began to take off in the early 1980s, and massive urban development began to take place in Guangdong and in the PRD region. As a consequence, the land-use distributions of the PRD have been undergoing rapid changes; the USGS land use may not reflect the actual situation of the PRD in the 1990s and certainly underestimates the urban coverage in today’s PRD.

Table 1. Contributions of the major vegetation classifications in the innermost 1.5-km D4.

<table>
<thead>
<tr>
<th></th>
<th>USGS (%)</th>
<th>HKPD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban</td>
<td>0.5</td>
<td>12.9</td>
</tr>
<tr>
<td>Cropland</td>
<td>45.6</td>
<td>22.7</td>
</tr>
<tr>
<td>Grassland</td>
<td>8.6</td>
<td>16.9</td>
</tr>
<tr>
<td>Forest</td>
<td>3.1</td>
<td>3.4</td>
</tr>
<tr>
<td>Water</td>
<td>42.0</td>
<td>42.1</td>
</tr>
<tr>
<td>Other</td>
<td>0.3</td>
<td>2.1</td>
</tr>
</tbody>
</table>

The 2003 land-use map reveals that about 13% of the land use in the domain is urban, as compared with the 0.5% of urban land use in the early 1990s from the USGS land-use map. The decrease in the percentage of cropland from 45.6% to 22.7% also reveals a transformation of the PRD from an agricultural region into an industrial base. Because the physical properties and parameters of cropland and urban areas are very different, it is expected that this rapid growth of the development should have a great impact on the local circulation.

In the standard MM5–Noah LSM, the green vegetation fraction is assigned by the monthly 5-yr climatological values of 0.15° AVHRR green vegetation cover data (Gutman and Ignatov 1998). This parameter is an important weighting factor for bare-soil direct evaporation and plant transpiration. In our MM5 simulations, the green vegetation fraction in the outer D1 and D2 domains was based on those monthly climatological data. However, there was a problem in interpolating the coarse-resolution AVHRR data into the MM5 inner 1.5-km domain that resulted in low and unrealistic green vegetation fraction near the coastal regions. Much of Hong Kong was assigned to a very low green fraction (20%–30%), which is not realistic. Taking advantage of the detailed PRD land-use data, we modified the green vegetation fraction in D3 and D4 according to the land-use category (see Table 2). Because PRD is located in a subtropical region, the seasonal variation of green fraction is very small; thus, the green vegetation can be regarded as an annually invariant field.

To produce a long-term development strategy for the next 30 years, the Planning Department of the Government of Hong Kong (HKPD) has carried out a detailed study on land-use patterns in the PRD region in 2003 (HKPD 2003). It produces an up-to-date 30-m-resolution land-use dataset in the PRD region. To be compatible with the MM5, this land-use dataset with 17 categories was remapped to corresponding USGS land-use 24-category vegetation categories. The mapping strategy is summarized in Table 2. Dominant land use of the 30-m HKPD land use is derived into the 30-s USGS grid based on the standard interpolation algorithm used by MM5. For example, if the water coverage is more than 50% at the grid, water will be assigned to that grid; if the water coverage is less than 50%, the grid is assigned with the maximum percentage category, excluding the water (Gou and Chen 1994).

The soil parameters in the Noah LSM, such as soil temperature, soil moisture, and soil water, were initialized from the 47-km U.S. Air Force Weather Agency’s real-time global Agricultural Meteorology Analysis Model (AGRMET) data. The land-model component of the AGRMET system also uses the Noah LSM. For the urban land use, we specifically fixed the soil moisture and soil water for all the soil layers as 0.1 m³ m⁻³, which is the same as that in default MM5 land surface parameters. The soil moisture was fixed for urban land use because the resolution of the AGRMET data is still very coarse relative to the inner domains; the soil parameters obtained from AGRMET may not have a good representation of the local characteristics in our finer domains, especially for the urban land use.

To investigate the impact of different land surface treatments on the local circulations, three 36-h MM5 experiments initialized at 0800 LST 30 October 2003 have been conducted to study a severe-air-pollution episode in Hong Kong and PRD. One MM5 experiment used the default USGS land-use map with the
MM5-slab simple land surface treatment (referred to as SLAB). The second one used the up-to-date 2003 land use with MM5-slab (referred to as SLAB-LANDU). The last experiment used the up-to-date 2003 land use with Noah LSM (referred to as URBAN-LSM), which has an enhancement on urban land-use treatment.

3. Effects of urban heat island in PRD simulated by three different approaches

a. Synoptic weather condition

On 1–3 November of 2003, a record-high air pollution episode occurred in Hong Kong and PRD with an API of 200, and the HKEPD issued the first severe-air-pollution warning since air-quality monitoring was introduced in 1995. Concentrations of air pollutants such as suspended particulates, sulfur dioxide, carbon monoxide, and nitrogen oxides reached a very high level and broke through the air-quality standard of Hong Kong. The record reading of ozone concentration topped at 402 parts per billion, which is 67% higher than the Hong Kong standard of 240 parts per billion. Wu et al. (2005) pointed out that a long-period accumulation of pollutants in PRD by land–sea-breeze circulation before the event caused this pollution episode. In fact, just before the episode, there was a half-month period of stationary weather in all of southern China and PRD. Under those weakly forced weather conditions, the land–sea breeze was the dominant circulation over Hong Kong and PRD.

Figure 4a shows the synoptic weather pattern on 0800 LST 31 October 2003 provided by the HKO. Under the influence of the dry northeast monsoon, the weather was generally calm and fair over southern China and PRD. Meanwhile, Tropical Storm Melor formed at the east of the Philippines and was moving northwest across northern Philippines toward Taiwan. From Hong Kong surface meteorological observations, the background wind over Hong Kong was weak easterly, and SBC was prominent during the episode period.

Figure 4b shows the 24-h simulated surface wind field and sea level pressure of D1 in the URBAN-LSM experiment corresponding to the same time as that of the HKO weather chart. The outer computational domain actually is larger than the region shown in the figure. However, to facilitate the model comparison with the HKO weather chart, we focus on the areas of east Asia. The simulated synoptic pattern generally agreed well with the HKO weather chart, and the location and intensity of Typhoon Melor is also simulated well by the model. This well-simulated synoptic pattern is an important criterion for a realistic simulation of local circulation. The simulated synoptic pattern of the SLAB and SLAB-LANDU experiments are similar to that of the URBAN-LSM experiment (not shown). Although these three experiments have similar synoptic patterns, the simulated local circulations are very different among them, as discussed in the next section.

b. Validation of simulated sea-breeze circulation features

The simulated surface wind fields (10 m AGL) of the three different land surface approaches on D4 (1.5-km...
grid spacing) are compared with observations at 1400 LST 31 October 2003 in Hong Kong (Fig. 5). Under the influence of the northeast high pressure system and Typhoon Melor (see Fig. 4a), the large-scale background wind over Hong Kong is weak easterly; but, as seen from observations (shown in Fig. 5), the local wind is dominated by SCB, which is pronounced in the western part of the New Territories and Lantau Island. Never-
theless, the simulations of large-scale background winds over the ocean are similar in these three MM5 experiments; locations and structures of the SBC front over the Pearl River Estuary and over Hong Kong are clearly different. The SLAB experiment depicted SBC to some extent (Fig. 5c), but the SBC front cannot penetrate farther inland because of its weaker land surface forcing. The western part of inland Hong Kong is still covered by background easterly wind. The SLAB-simulated SBC front is located in the Pearl River around 15 km from the western seashore of Hong Kong. Based on the up-to-date land-use characteristics, the SLAB-LANDU experiment (Fig. 5b) seems to capture the SBC in western Hong Kong but does not reproduce the observed SBC structure in inland Hong Kong. By contrast, in the URBAN-LSM experiment, the SBC feature is simulated well (Fig. 5a), and the strong SBC supersedes the background easterly wind. As a result, westerly wind is well developed in the western part of Hong Kong and southerly wind is prominent over the seashore between Lautau Island and Hong Kong Island.

To verify the temporal structure of the simulated winds and the arrival time of the SBC, temporal variations of the observed and simulated surface winds at three stations are shown in Fig. 6. Waglan Island (WGL), which is located 10 km southeast of Hong Kong Island, provides large-scale synoptic background-wind information. Hong Kong International Airport (HKA) and Lau Fau Shan (LFS), which are located in northwest Lautau Island and the northwest New Territories, respectively, are selected to provide the temporal SBC features for verification. As shown in Fig. 6, observed background easterly winds are persistent for the whole 36-h simulation period at WGL. The URBAN-LSM experiment generally captured these synoptic wind features well. On the other hand, the winds patterns simulated by the SLAB-LANDU and SLAB experiments have around 10° systematic biases for wind direction. At HKA and LFS, SBC is dominant from 1100 to 1800 LST and is further enhanced on the second day (31 October). The SLAB experiment only simulated the weakening of the easterly background wind but was not able to predict correctly the wind direction changes as observed at the station. The SLAB-LANDU experiment has better timing of the sea breeze than does the SLAB. Among the three experiments, the URBAN-LSM produced the best spatial simulation of the sea-breeze features and the timing of the sea breeze was captured well, especially on the second day. Similar temporal verifications have been performed on other stations at the western part of Hong Kong and the results are similar to those at HKA and

![Fig. 5. Simulation and observation of surface wind field valid at 1400 LST 31 Oct 2003 given by (a) URBAN-LSM, (b) SLAB-LANDU, and (c) SLAB experiments.](image)
LFS. From the verification of surface winds, it is clear that an advanced land surface model, which provided better simulations of the surface heat flux and forcing, was able to reproduce the pattern of observed features of SBC in Hong Kong. The vertical cross sections of wind streams across the Pearl River at a latitude of 22.55° N at 1400 LST given by the three experiments are shown in Fig. 7. The exact location of this cross section is also marked (line AA’/H11032) in Fig. 1. The right side of the vertical cross section is Shenzhen, which is a highly urbanized city in PRD. From the URBAN-LSM (Fig. 7a), it can be seen that the afternoon sea-breeze circulations were well developed: several closed circulations are developed within the PBL over the coastal region, of which the most prominent circulation zone is located over the Pearl River Estuary (113.5°–114.0°E). The extension of this circulation zone can reach to 50 km in the horizontal dimension and to 1.5 km in the vertical dimension. It is also interesting to see that not only the SBC, but also the urban heat island circulation (UHIC) has been generated between the urban areas in Shenzhen (around 114.15°E) and the surrounding region. Upward vertical velocity reaches to 0.6 m/s in the urban area; by contrast, downward 0.4 m/s vertical motion is occurring in the surrounding rural areas. By contrast, these SBC and UHIC were not well developed by experiments SLAB-LANDU (Fig. 7b) and SLAB (Fig. 7c).

c. Spatial structures of UHI in PRD

Tables 3 and 4 summarize the comparison between observed and modeled surface temperature at 33 monitoring stations in Hong Kong. Table 3 lists all urban stations, and Table 4 lists all rural stations. We define a monitoring station as urban if it is located in an urban grid in the innermost 1.5-km D4. A monitoring station that is not located in the urban grid is regarded as a rural station. The tables are sorted by station mean temperature (36-h average) in descending order. Under the generally fair weather conditions in Hong Kong, the mean surface air temperature of the station measurements varied from 17° to 26°C. Some stations, such as the Peak (VP1), Tate’s Cairn (TC), and Tai Mo Shan (TMS) stations, are located in the mountainous region and generally record lower temperature. Temperatures in urban areas such as Mong Kok (MK), Sham Shui Po (SP), and HKA are generally 2°–3°C higher than those of the rural areas such as Tap Mun (TAP), Wagland Island (WGL), and Sai Kung (SKG).

The model results for each station from these three experiments (URBAN-LSM, SLAB-LANDU, and SLAB) were compared on an hourly basis with obser-
vations; mean error (ME) and root-mean-square error (RMSE) were calculated. The sample size of the statistic is 36 from 0800 LST 30 October to 2000 LST 31 October 2003. The SLAB surface air temperature has large cold biases and RMSE, especially for urban areas. The SLAB-LANDU improves the model performance by reducing the averaged cold bias and averaged RMSE. The URBAN-LSM experiment produced the best agreement with observations and the urban land-use enhancements reduced the cold bias in urban areas. When compared with SLAB, both the averaged ME and the averaged RMSE were reduced from $-1.22^\circ$ to

Fig. 7. Vertical cross sections along the line AA’ in Fig. 1 valid at 1400 LST 31 Oct 2003 given by (a) URBAN-LSM, (b) SLAB-LANDU, and (c) SLAB experiments.
−0.5°C and from 2.05°C to 1.01°C, respectively, for urban areas (Table 3).

The distribution of UHI in PRD is clearly seen in Fig. 8a, which shows the spatial variance of surface brightness temperature from the 5-km-resolution Moderate-Resolution Imaging Spectroradiometer (MODIS) valid at 0200 LST 31 October 2003. Spatial variance is the temperature at each grid point minus the domain-averaged temperature. At midnight in PRD, temperature in urban cities such as Guangzhou, Foshan, and Dongguan was considerably higher than in the surrounding rural areas. Figure 8b shows the URBAN-LSM-simulated UHI pattern. Temperatures over ocean and urban areas are about 4°C higher than the domain-averaged temperature at midnight. Similar to the MODIS data, the main high-temperature region is around Guangzhou. This type of UHI pattern was captured well by the simulations of the URBAN-LSM experiment. However, in the SLAB experiment, nocturnal UHI is less developed (Fig. 8d), the temperature variation between rural and urban areas is very small, and its high-temperature zones are only over the ocean.

### Table 3. Performance statistics of simulated surface temperatures at urban stations in Hong Kong.

<table>
<thead>
<tr>
<th>Station identifier</th>
<th>Height (m)</th>
<th>Observation ME</th>
<th>Observation Std dev</th>
<th>URBAN-LSM ME</th>
<th>URBAN-LSM RMSE</th>
<th>SLAB-LANDU ME</th>
<th>SLAB-LANDU RMSE</th>
<th>SLAB ME</th>
<th>SLAB RMSE</th>
</tr>
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<tr>
<td>MK</td>
<td>3</td>
<td>26.0</td>
<td>1.47</td>
<td>−1.23</td>
<td>1.45</td>
<td>−1.55</td>
<td>2.94</td>
<td>−1.81</td>
<td>2.95</td>
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<tr>
<td>SP</td>
<td>17</td>
<td>25.1</td>
<td>1.53</td>
<td>−0.75</td>
<td>1.18</td>
<td>−1.06</td>
<td>2.58</td>
<td>−1.36</td>
<td>2.66</td>
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<td>HKA</td>
<td>8</td>
<td>24.9</td>
<td>1.46</td>
<td>0.01</td>
<td>0.66</td>
<td>−0.65</td>
<td>2.20</td>
<td>−1.93</td>
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<tr>
<td>TW</td>
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<td>24.9</td>
<td>2.08</td>
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<td>1.21</td>
<td>−1.23</td>
<td>1.85</td>
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<td>−0.78</td>
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<td>−0.32</td>
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### Table 4. Performance statistics of simulated surface temperatures at rural stations in Hong Kong.

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<th>Station identifier</th>
<th>Height (m)</th>
<th>Observation ME</th>
<th>Observation Std</th>
<th>URBAN-LSM ME</th>
<th>URBAN-LSM RMSE</th>
<th>SLAB-LANDU ME</th>
<th>SLAB-LANDU RMSE</th>
<th>SLAB ME</th>
<th>SLAB RMSE</th>
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</table>
The UHI pattern given from the SLAB-LANDU (Fig. 8c) experiment is similar to that of SLAB (Fig. 8d), indicating that a good simulation of UHI not only needs an up-to-date urban land-use distribution but also needs realistic parameterizations for urban land use.

Figure 9 shows domain-averaged diurnal cycles of ground temperature and PBL height simulated for the urban and rural areas by URBAN-LSM. Rural areas are defined as all of the land points except those that are urban. From the figure, urban areas are generally 2°–4°C warmer than rural areas, and the UHI is prominent for both daytime and nighttime. These 2°–4°C temperature differences during the daytime appear to correspond to the 200-m-deeper PBL in urban areas; however, the nocturnal urban PBL depth is not very different from that over the rural areas. Figure 10 shows the corresponding time series of the surface energy budgets from the URBAN-LSM simulation. Relative to the rural areas, the dry urban areas produced smaller latent heat (evaporation) and larger sensible and ground heat fluxes. The larger sensible heat flux is responsible for the daytime UHI, and the larger ground heat flux (i.e., more heat is stored in the ground during daytime and later released during nighttime) is responsible for nocturnal UHI. For urban areas, the latent heat fluxes are generally small except for a short period right after rain, and therefore the incoming radiation is largely partitioned into sensible heat and ground heat fluxes. Sensible heat flux transfers heat to the atmosphere while ground heat flux transfers heat downward to the subsurface. Both play a role in modulating UHI (e.g., large ground heat fluxes decrease sensible heat fluxes for a given net radiation), but the temperature fluctuation is largely influenced by sensible heat flux.
which is in general 50–200 W m\(^{-2}\) higher than ground heat fluxes. Hence, the difference in the PBL height between urban and rural areas is caused by the difference in their sensible heat fluxes. In the evening over urban areas, a large amount of heat transferred to the subsurface during daytime is transferred back to the ground surface by ground heat fluxes and then to the atmosphere through slightly positive sensible heat fluxes, which affect the nocturnal temperature in urban areas. During nighttime, ground heat fluxes are as large
as, or slightly higher than, sensible heat fluxes. Sometimes, sensible heat fluxes are negative (i.e., heat transferred from the atmosphere to the surface), and so positive (upward) ground heat fluxes dominate heat transfer in the nocturnal urban areas.

4. Impacts of urban land-use change on regional meteorological behavior in the PRD

We have seen in the last section that URBAN-LSM, with an enhancement of urban land-use treatment, was
able to capture the major features of the observed surface temperature and wind structures in the PRD. In this section, we utilize the coupled MM5–Noah LSM to conduct several sensitivity experiments by changing the inner domains’ (D3 and D4) land use to examine the urbanization effect on meteorological conditions over the PRD. In the first sensitivity test (referred to as NO-URBAN), all urban land-use points in the URBAN-LSM control experiment were replaced by dry cropland (USGS category 2). In the second sensitivity test (referred to as 2X-URBAN), all cropland points were converted into urban land use, and it approximately doubles the total urban area in the simulation domains. In the third sensitivity test (ALL-URBAN), representing an extreme case, all land points were assigned as urban land use, so that the domains only have either urban land use or a water body. All three experiments are conducted using initial conditions and physics schemes that are identical to those of the CONTROL simulation.

a. Impacts of urban land-use change on sea-breeze circulation

The generation of land–sea-breeze circulations is largely controlled by the temperature differences between the ocean surface and the land surface. Because the UHI produces a higher temperature, the change in the distribution of urban area could affect airflow patterns within the region, particularly during daytime when higher sensible heat flux and higher temperature of urban areas could have a strong influence on local circulations. Figure 11 shows the difference of surface horizontal wind at 1400 LST 31 October 2003 between CONTROL and NO-URBAN (Fig. 11a) and between ALL-URBAN and NO-URBAN (Fig. 11b). Relative to NO-URBAN simulations, the CONTROL produced a stronger SBC in the eastern Pearl River coast; this is because most of that area has been developed into urban areas in the last 20 yr, which produced a higher temperature, and hence intensified SBC. Therefore, it is not surprising that in ALL-URBAN, because of an even higher density of urban areas, SBC penetrated much farther inland along the eastern coast. In addition, southeasterly SBC in the western Pearl River Estuary is intensified by the larger temperature contrast between water and the land.

b. Impacts of urban land-use change on PBL temperature

From section 3c, there is clear evidence of a temperature increase in the overall PRD areas as a result of urbanization. In term of vertical temperature profile at 1400 LST, a fully converted urban land use in the PRD produced an average of 1.5°C higher near-surface temperature than that of the current land-use distribution in the PRD. The influence of land use can reach as high as 2 km during daytime. It is expected that in the next decade the distribution of urban area will be doubled; the surface temperature would increase by about 0.5°C as a result. On the other hand, without urban areas, the domain-averaged temperature would be reduced by about 0.5°C.

Last, we note that the focus of this study is to use case studies to discuss the impact of past land-use changes on the circulation over the PRD. For future studies, it is of interest to study further the impact of different land-use types (e.g., changing urban/cropland areas to forests) on the overall land–sea-breeze circulation or to conduct longer simulations (e.g., 1 month over 1992 in comparison with the same month over 2003) to provide longer statistics to confirm the results.

5. Conclusions

In this paper, three approaches of land surface treatments were used to examine the evolution of local and regional SBC conducive to a high-air-pollution episode that occurred in Hong Kong and the PRD on 1–3 November 2003. In the current MM5, the 1993-based USGS land-use data underestimate the urban-area growth in the rapidly expanded PRD region. Using this MM5 default land-use map and a simple slab land model, MM5 generated a weak SBC because of insufficient land surface forcing over urban areas. Moreover, a large temperature cold bias is found because of unrealistic land-use distribution. By contrast, using the MM5–Noah LSM, along with an up-to-date high-resolution land-use map and enhancements of urban land-use treatment, we were able to capture major features of the observed surface temperature and wind flow patterns in the PRD.

The role of urban land-use distribution and its associated urban heat island in modulating local and regional airflow patterns in the PRD was investigated. It is demonstrated that a stronger urban heat island in the PRD increases the differential temperature gradient between urbanized areas and the nearby ocean surface and hence enhances the mesoscale SBC. As a consequence, the SBC front penetrates farther inland to overcome the prevailing easterly flow in the western part of inland Hong Kong. It is clear that understanding the modifications of temperature and wind direction in the boundary layer in the PRD metropolitan and rural areas and correctly predicting them is imperative to improve our ability to predict air quality and disper-
Fig. 11. Difference of horizontal wind vector at 1400 LST 31 Oct 2003 for (a) CONTROL – NO-URBAN and (b) ALL-URBAN – NO-URBAN.
A precise description of land use in urban and rural regions proves critical toward establishing an urban air-pollution prediction system. Through the sensitivity studies, the impact of urbanization on meteorological conditions over the PRD is examined. The results show that further urbanization could strengthen the SBC. With higher sensible heat fluxes, the temperature in the lowest 2-km atmosphere over urban areas can increase by about 1.5°C.

The results also suggest that the air-pollution meteorological behavior of the PRD region is strongly influenced by local sea-breeze circulation. The sea-breeze convergence region is identified as the principal feature contributing to the regional haze problem. The recirculation of pollutants caused by enhanced land–sea-breeze circulations may be an important aspect of the local air-pollution meteorological behavior that is worthy of further investigation.

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