IMPROVEMENT OF AIR QUALITY MODELING IN HONG KONG BY USING MM5 COUPLED WITH LSM

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1. INTRODUCTION

Accompanied with the rapid urbanization and industrial development, Hong Kong and the Pearl River Delta (PRD) region of China have been experiencing air pollution problems such as episodic levels of ozone (O_3) and particulate matter (PM), and deterioration in visibility in recent years (Huang et al., 2005; Fung et al., 2005). For instance, Hong Kong had 50 days of air pollution episodes in 2004 (an air pollution episode day is referred to as a day with an air pollution index, API, higher than 100), compared with 31 days in 2003. Rapid economy development has resulted in a drastic increase of anthropogenic emissions and the region has been fully developed into much more urbanized areas. For example, emissions of NO_x and SO_2 increased by 28% and 12%, respectively, over the PRD region from 1990 to 1995, and are anticipated to increase by 138~171% and 51~173%, respectively, from 1995 to 2020 (Streets and Waldhoff, 2000). By 2000, urbanization level in PRD reached nearly 50%. With this scale of urbanization, local meteorological conditions such as local wind circulations, have changed remarkably, eventually, have a significant impact on the occurrences of air pollution events in Hong Kong and the PRD region.

Meteorology is well known to be an important factor affecting air quality. It encompasses many atmospheric processes that control or strongly influence the formation, transport, diffusion, and accumulation of air pollutants (both gases and PM). Photochemical models generally require temporally, and spatially solved wind fields, temperature, humidity, mixing depth, solar actinic flux, turbulence intensity, and surface fluxes for heat, moisture, and momentum. Therefore, realistic simulations of meteorological fields are typically important for modeling air quality.

The purpose of this study is to improve air quality modeling by providing reasonable meteorological inputs with a mesoscale meteorological model (MM5) coupled with an advanced land surface model (LSM), the National Centers for Environmental Prediction, Oregon State University, Air Force, and Hydrologic Research Lab – National Weather Services (NOAH) LSM, which has several enhancements on urban land-use treatments and a local up-to-date high-resolution land-use dataset (Lo et al., 2004). MM5 provides the external forcing to the NOAH LSM with simulations of temperature, near-surface winds, humidity, precipitation, and surface radiation. The NOAH LSM, in turn, provides MM5 with surface sensible heat flux, latent heat flux, and

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skin temperature as lower boundary conditions. This will be helpful to realistically simulate local wind circulations, and the vertical structure of the planetary boundary layer (PBL) (Chen and Dudhia, 2001). A two-day ozone episode (an ozone episode day is referred as to a day when hourly O_3 concentration is higher than 120 ppb) occurring from 22 to 23 of October 2003, will be investigated with both the Hong Kong Environmental Protection Department (HKEPD) model, Pollutants in the Atmosphere and Their Transport over Hong Kong (PATH), and the U.S. EPA Models-3/Community Multiscale Air Quality (CMAQ) modeling system (Byun and Ching, 1999). It is used to illustrate the improvements of MM5 simulations coupled with LSM on meteorological fields, and subsequent impacts on predictions for ozone and other pollutants from both PATH and CMAQ.

2. MODEL CONFIGURATIONS

The PATH model system is a three-dimensional regional photochemical and transport model. It consists of three modules: the fifth-generation Pennsylvania State University (PSU) and the National Center for Atmospheric Research (NCAR) Mesoscale Modeling System, MM5 (Grell et al. 1994); an emission processing module (EMS-95; Emigh and Wilkinson, 1995); and a photochemical model, The San Joaquin Valley Air Quality Study (SJVAQS) and the Atmospheric Utility Signatures Predictions and Experiments Study (AUSPEX) Regional Modeling Adaptation Project (SARMAP) Air Quality Model (SAQM) (Chang, et al., 1997).

MM5 is a community mesoscale model widely used for numerical weather prediction, air quality studies, and hydrological studies (Warner et al., 1991; Mass and Kuo, 1998). The NOAH LSM has been implemented in MM5 by Chen and Dudhia (2001).

The emission inventories used in this study are generated by HKEPD with EMS-95 based on the emission datasets in year 2001 (Huang, et al., 2005). The emission inputs of gaseous species used for PATH are mapped to those of CMAQ.

The Carbon Bond-IV (CB-IV) chemical mechanism is used to simulate gas-phase chemistry in both PATH and CMAQ. In PATH, the Binkowski-Roselle particulate model is used for the prediction of RSP mass (Binkowski et al., 2003). The particle species are considered to fall within three size categories for mass distribution: Ultra-fine (nuclei) mode (< 0.1 μm), accumulation mode (0.1-2.5 μm), and coarse mode (2.5-10 μm). In CMAQ, the particle-size distribution is represented as the superposition of three lognormal sub-distribution. CMAQ uses ISORROPIA to simulate thermodynamic equilibrium for inorganic species, and uses reversible absorption parameterization for organic species. In addition, nucleation, coagulation, condensational growth, gas/particle mass transfer, cloud processing, and deposition etc. are also included in CAMQ (Byun and Ching ,1999).

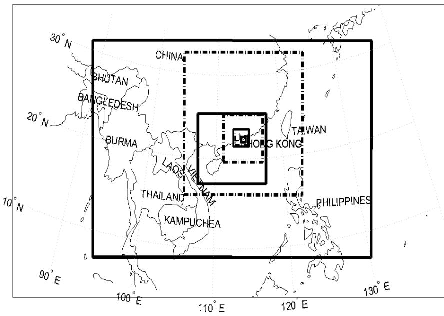

Fig. 1. Settings of four nested domains in MM5 (solid line) and in SAQM (dashed line); resolutions from the outmost to the innermost domains are 40.5, 13.5, 4.5, and 1.5 km, respectively.

Both MM5 and air quality models (PATH and CMAQ) are run with a configuration of four nested domains, as shown in Figure 1. The horizontal resolutions from the outermost domain to the innermost domain are 40.5, 13.5, 4.5, and 1.5 km, respectively. For technical reasons, the air quality model (SAQM) are set up on four nested square domains with each domain containing 49 × 49 grid cells, whereas MM5 and EMS-95 are set up on four nested domains with the following cell numbers along the east-east and north-south directions: 115 × 75, 85 × 73, 61 × 55, and 61 × 55, respectively. In the vertical direction, MM5 has 26 unequal sigma layers, defined unequally from the ground to the model top (100 hpa), while SAQM has 15 sigma layers, with the lowest ten layers coinciding with those of MM5. CMAQ has the same domain settings as SAQM.

3. SIMULATION RESULTS

An O_3 episode was observed from 22 to 24 October 2003 over the Hong Kong territory. The synoptic patterns were characterized by a high pressure system governing the Northern and the Eastern China, and the typhoon Ketsana traveling over the northwestern Pacific. These types of synoptic patterns had caused large scale air stagnation over Hong Kong, bringing in weather conditions (e.g., stable atmospheric layer, northeasterly-northwesterly winds, higher temperature, and solar radiation) that were conducive to the O_3 formation and buildup. The highest O_3 concentrations of 134.4 and 126.2 ppb were recorded by the HKEPD at Tung Chung (TC) station on 22 and 23 of October, respectively (the location shown in figure 2).

3.1 Improvement of meteorological simulations with MM5 coupled with LSM and new land use datasets

The three-day period from 0200 LST on 22th (1800 UTC on the 21th) to 0200 LST on 25th (1800 UTC on the 24th) October 2003 is selected as the simulation period for MM5. The initial and boundary conditions for the outmost domain are provided by the six hourly Global Final (FNL) Analysis with a horizontal resolution of 1.0 × 1.0 degree in latitude and longitude.

Two-way nesting is applied to the MM5 domains. The medium-range forecast (MRF) PBL scheme for four domains, the Grell cumulus parameterization scheme (for domains 1 and 2, none in other domains) are employed in the MM5 simulations. High-resolution (as fine as 30 m) land use data, originally was complied by the Planning Department of the Hong Kong government and then was reformatted to replace default 30-second land use dataset in MM5 over Hong Kong and the PRD region.

Compared with standard MM5 model simulation without LSM, a MM5 simulation coupled with both LSM and new land use data provides a better agreement with surface wind observations. Comparisons at Tung Chung (TC) and Tap Mun (TM) stations are shown in Figure 3. The standard MM5 run cannot solve the reversed wind patterns, i.e. sea breeze during daytime, and also greatly overpredicts surface wind speed (see Figures 3.a and 3.b). But main features of surface winds are captured when the LSM model and new land use are applied to MM5 simulations (shown in Figures 3.c and 3.d). This could be related to correctly treating the land surface processes by MM5 coupled with LSM.

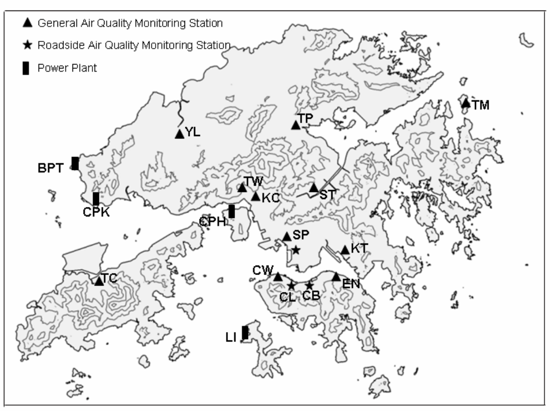

Fig.2. HKEPD air quality monitoring stations used in this study; the topography of Hong Kong is also shown with contours at 200 m intervals.

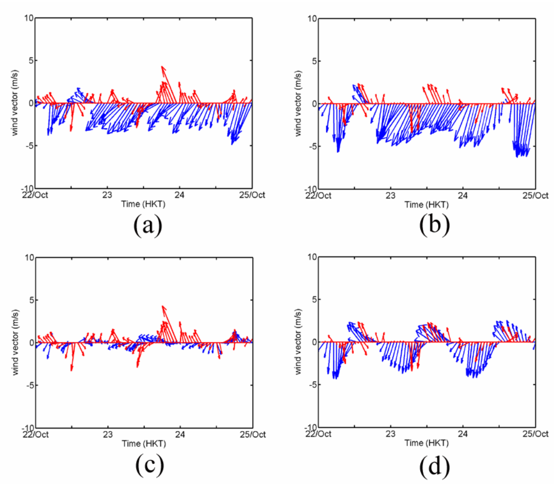

Fig. 3. Observed surface winds (red) compared with the MM5 simulations (blue) without LSM at (a) Tung Chung and (b) Tap Mun, and with LSM at (c) Tung Chung and (d) Tap Mun.

TABLE 1. Performance statistics (surface winds) averaged over fourteen stations calculated for the MM5 simulations coupled with LSM and without LSM, where ws is wind speed (m/s) and wd is wind direction (°).

	Mean obs ws	Mean model ws	Std dev obs wd	Std dev model wd	Std dev Obs ws	Std dev model ws	Rmsd ws	Index of agree. ws	Index of agree. wd
No LSM	2.2	4.3	75.3	46.0	1.1	1.5	2.9	0.38	0.55
LSM	2.2	3.1	75.3	62.2	1.1	1.1	1.8	0.54	0.63

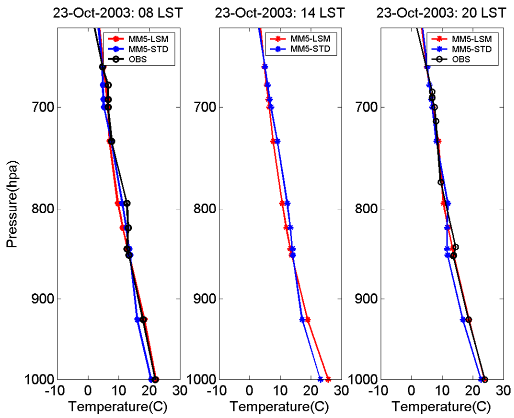

Fig.4. Simulated (from domain D4) and radiosonde soundings reported (black) temperature profile at Kings Park (Hong Kong) for Oct. 22, 2003. Soundings were only available at 00 and 12 UTC (08 and 20 HKT). (red: the MM5 simulation with LSM; blue: the MM5 simulation without LSM).

The performance of MM5 simulations of surface wind speeds and wind directions is further evaluated using several statistical parameters. They include the observed and predicted mean and standard deviation of wind speed and wind direction (std dev), the root-mean-square difference (rmsd), the index of agreement. The average performance statistics of MM5 without LSM and with LSM at fourteen Hong Kong observatory monitoring stations is presented in Table 1. Coupling NOAH LSM to MM5 and application of new land use map have much better performance on modeling of surface winds compared with the MM5 simulation without LSM.

In Figure 4, compared with the simulation of MM5 without LSM, the simulation of MM5 coupled with LSM and new land use, shows a better agreement with temperature profiles observed at Kings Park (Hong Kong) on Oct. 23, 2003, particularly for lower levels below 850 hPa where the influence on air pollution is the greatest. The atmosphere was mostly stable below 850 hPa (about -0.57 °C/100 m) in the morning (08 LST) when the sounding was available for comparison. During mid-afternoon when the pollution was more severe, a close examination of the simulated profile at 14 LST shows that the lapse rate was -0.80°C/100 m and conditionally unstable below 850 hPa (~1500 m above ground level (AGL)). This suggests that the model was able to simulate the subsidence effect associated with the typhoon and the anticyclone, which sustained a stable atmospheric boundary layer.

Therefore, coupling LSM to MM5 provides better agreements with observations for both surface wind patterns and temperature profiles. The subsequent effect on modeling of air quality will be investigated in the next section.

3.2 Improvement of air pollutant simulations

Both PATH and CMAQ simulations covered 68 hrs from 0400 LST on 22 October 2003 through 0000 LST on 25 October 2003. The first day simulation is considered as a spinup run to provide initial conditions for simulations with both models.

Figure 5 shows the spatial distributions of hourly O_3 mixing ratios predicted by PATH in domain 3 (i.e., PRD) and domain 4 (i.e., Hong Kong). For the case of MM5 simulation without LSM, PATH predicts high O_3 mixing ratios of > 120 ppb in the east side of the Pearl River Estuary (see Fig. 5a). But the maximum value of O_3 did not exceed 85 ppb over the Hong Kong territory. No sea breeze was predicted by MM5 along the coastal region of the territory.

However, a convergence zone was predicted by the MM5 simulation with LSM, especially, in Lantau Island, the western portion

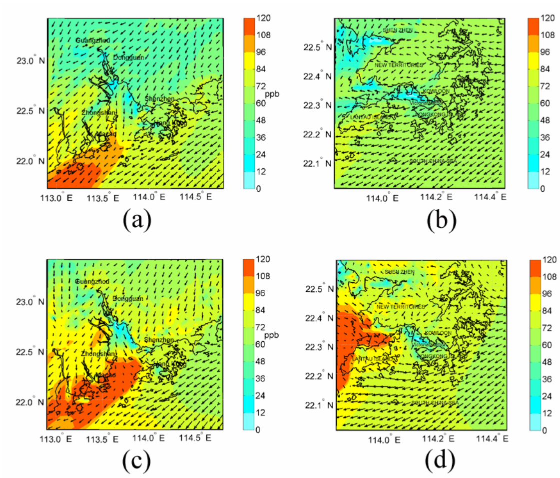

Fig. 5. The spatial distribution of hourly average O_3 mixing ratio at 1600 LST on Oct. 22, 2003, PATH/SAQM are driven by MM5 simulations without LSM (a) in PRD (D3), and (b) in Hong Kong (D4); and with LSM (c) in PRD (D3), and (d) in Hong Kong (D4).

of the territory (D4). Air pollutant was trapped and elevated to higher levels. An O_3 plume with mixing ratios higher than 120 ppb occurred over this region. In addition, ozone was built up to much higher levels throughout the territory.

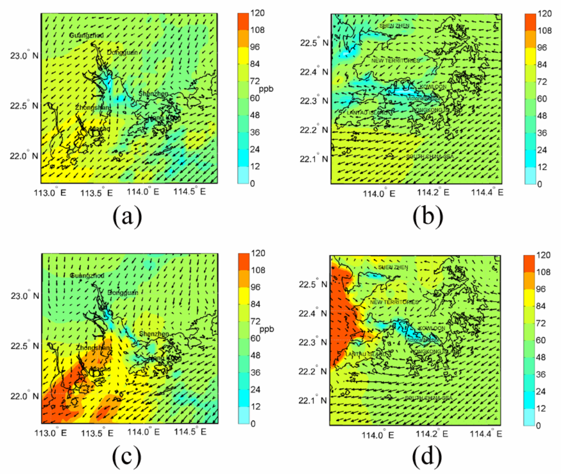

Fig. 6. The same as Fig. 5 but for CMAQ.

Similar improvements are also found in CMAQ simulations for the LSM case, as shown in Figure 6. Thus, correctly solving surface wind patterns (i.e., the reversed winds) and other meteorological fields is particularly important to capture high levels of air pollutants.

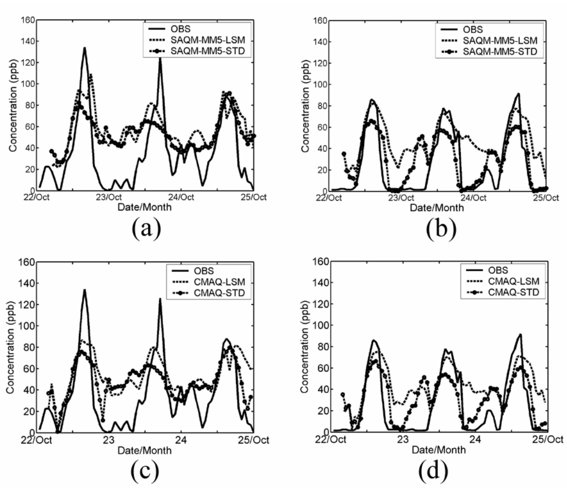

Fig. 7. The time series of observed and predicted O_3 mixing ratios on October 22-24, 2003 by SAQM at (a) Tung Chung, and (b) Sha Tin; and by CMAQ at (c) Tung Chung, and (d) Sha Tin.

Figure 7 shows the time series of observed and simulated ozone maxing ratios at two HKEPD monitoring stations, Tung Chung (TC) and Sha Tin (ST), respectively (their locations shown in Figure 2). Compared with the standard MM5 simulations (i.e. without LSM), both SAQM and CAMQ simulations with MM5-LSM show better agreement with peak ozone at these two stations, but still underestimate the peak values at Tap Mun and Tung Chung stations, and overestimate ozone maxing ratios during the nighttime. This could be related to uncertainty of emissions. Similar comparisons are performed for other HKEPD monitoring stations, but not shown here.

4. Summary

PATH and CMAQ are applied to investigate an ozone episode on October 22-24, 2003 in Hong Kong and the PRD region. The simulations of MM5 with NOAH LSM show a better agreement with meteorological observations such as surface winds, temperature profiles, etc., in comparison of those of MM5 without LSM. The convergence zone caused by reversed winds, i.e., sea breeze, is favorable for trapping and accumulation of air pollutants. The correctly treating land surface process is particularly important to resolve the atmospheric boundary layer where air pollutants are trapped. Consequently, the surface ozone simulations have been improved in terms of the peak ozone when MM5/NOAH LSM is used to generate meteorological fields for air quality models. However, the impact of MM5/NOAH LSM on PM modeling is still under investigation.

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