J1.2 PROCESS ANALYSIS OF DIFFERENT SYNOPTIC PATTERNS OF O_3 EPISODES IN HONG KONG

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1. Introduction

Hong Kong is situated at the southeastern coast of China and adjoining the rapidly-developing Pearl River Delta (PRD) of China. The rapid urbanization and industrial development have resulted in a remarkable increase of anthropogenic emissions in the PRD region over the past two decades. Between 1990 and 1995, NO_x emissions increased by 21% over the PRD region, and are anticipated to increase by 100~160% between 1995 and 2020 (Streets and Waldhoff, 2000). As a result, the PRD region and adjoining Hong Kong have been suffering from more frequent and serious air pollution events including episodic levels of surface O_3 and fine particles (e.g., Huang et al., 2005a, b). For instance, 50 high air pollution days occurred in Hong Kong in 2004 (a pollution day is referred as to a day with the air pollution index, API, higher than 100[1], compared with 31 days in 2003. The days of air pollutant episodes (API ≥ 100) increase significantly in Hong Kong from 1999 to 2004, as shown in Figure 1. High levels of O_3 are found to be the most important contributor to the occurrence of air pollutant episode events in all general monitoring stations over the region. Thus, episodic levels of O_3 will continue to represent one of major challenges in controlling air quality in Hong Kong and the PRD region.

In this study, a three-dimensional (3-D) photochemical and transport model, Pollutants in the Atmosphere and their Transport over Hong Kong (PATH), is applied to investigate different synoptic patterns of O_3 episodes over Hong Kong. Process analysis method embedded in the San Joaquin Valley Air Quality Study/Atmospheric Utility Signature Predictions and Experiments (SJVAQS/AUSPEX) Regional Modeling Adaptation Project (SARMAP) air quality model (SAQM), is used to identify the relative contributions of local photochemical products versus regional transport during all O_3 episodes from 2000 to 2004.

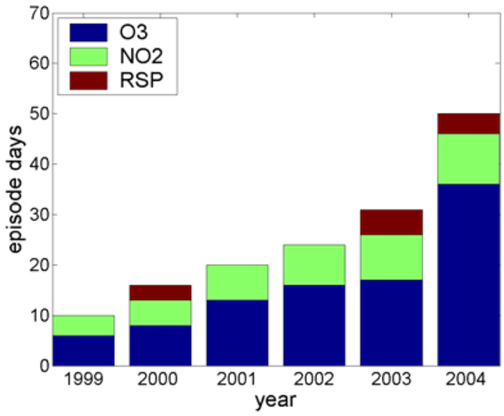

Figure 1. Trends of air pollution episode days (API ≥ 100) and the contributing pollutants (O_3, NO_2, RSP) in Hong Kong during 1999-2004.

2. Model Description

The PATH model system consists of three submodels: the fifth-generation Pennsylvania State University (PSU) and the National Center

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[1] API > 100, for example, means hourly O_3 > 120 ppb, or hourly NO_2 > 300 $\mu g m^{-3}$, or 24-hr respirable suspended particulate (RSP) > 180 $\mu g\ m^{-3}$.

for Atmospheric Research (NCAR) Mesoscale Modeling System, MM5 (Grell et al., 1994); an emission processing model (EMS-95; Emigh and Wilkinson, 1995); and a photochemical model, SAQM (Chang, et al., 1997). The PATH model has been extensively tested and verified by the Hong Kong Environmental Protection Department (HKEPD), and currently employed to modeling air pollution in Hong Kong and the PRD region (e.g., Huang et al., 2005a, b, c).

Both MM5 and SAQM are applied with a configuration of four nested domains, as shown in Figure 2. The horizontal resolutions from the outermost to the innermost domains for both models are 40.5, 13.5, 4.5, and 1.5 km, respectively. For SAQM simulations, each domain contains 49 × 49 grid cells, whereas for MM5 and EMS-95 simulations, the numbers of grid cells along the west-east and north-south directions are 115 × 75, 85 × 73, 61 × 55, and 61 × 55 grid cells for the four nested domains from the outermost to the innermost, respectively. In the vertical direction, 26 sigma layers are used in the MM5 simulation, defined unequally from the ground to the model top (100 hpa), while 15 sigma layers are used in SAQM simulations, with the lowest ten layers coinciding with those of MM5.

The up-to-date high-resolution (30 m) land use data, originally complied by the Planning Department of the Hong Kong Government (HKPD), is reformatted to supersede those of default 30-arc second in MM5 over Hong Kong and the PRD region. Much larger urban areas (increased by a factor of about 24) have been developed over the PRD region in 2003 as compared with standard MM5 V3.6.3 24-category land use (1993) (not shown in here). With this scale of urbanization, anthropogenic emissions have increased significantly, while local meteorological conditions including land sea breeze and heat island effects have changed remarkably, eventually, have a significant impact on the occurrences of air pollution events in Hong Kong and the PRD region (Fung, et al., 2005; Lo et al., 2005).

In addition, analysis nudging and observational nudging are applied to the outmost domain (D1) and the innermost domain (D4), respectively, as suggested by Stauffer and Seaman (1994).

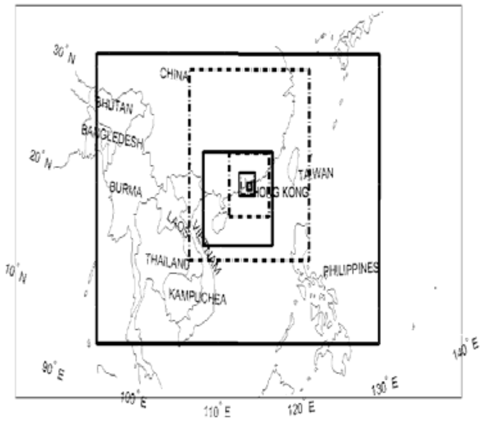


Figure 2. Settings of four nested domains for MM5 (solid line) and SAQM (dashed line); resolutions from the outmost to the innermost domains are 40.5, 13.5, 4.5, and 1.5 km, respectively.

The emission inventory for the PATH system is complied with EMS-95 based on the data in year 2001. The inventory consists of five categories of emission sources: point, mobile, area, shipping, and biogenic sources. Emissions in the first two domains (D1 and D2) are the same as those in previous study (Huang et al., 2005a), but emissions in PRD (D3) and Hong Kong (D4) are updated using the emission inventory of year 2001.

3. Process Analysis Method

Process analysis is a diagnostic tool, commonly used in different air quality models, such as the PATH (Huang et al., 2005a, b, and c), the Model-3 Community Multiscale Air Quality (CMAQ) Modeling System (Byun, et al., 1999; Binkowski and Roselle, 2003), and the Comprehensive Air Quality Model with extensions (CAMx) (ENVIRON, 2004). It quantifies the impacts of individual physical processes and chemical reactions on the formation of O_3 and other species. Two process analysis methods are embedded in SAQM: integrated process rate (IPR) analysis, and integrated reaction rate (IRR) analysis. The former assesses the effects of all physical processes and the net effect of chemistry, while the latter tracks individual gas-phase chemical transformation pathways to identify the relative contributions of individual chemical reactions to chemical species of interest (e.g., O_3). IPR can be used to identify the change in species concentrations due to different physical and chemical processes, as shown in the following partial differential equations.

$$\frac{\partial C_i}{\partial t} = -\left[\frac{\partial}{\partial x}(uC_i) + \frac{\partial}{\partial y}(vC_i)\right] + \left[-\frac{\partial}{\partial z}(wC_i) + \frac{\partial}{\partial z}(K_e \frac{\partial C_i}{\partial z})\right] + (P_{\text{chem}} - L_{\text{chem}}) + E + \left(\frac{\partial C_i}{\partial t}\right)_{\text{cloud}} + \left(\frac{\partial C_i}{\partial t}\right)_{\text{dry}} \quad (1)$$

, where C_i is the concentration of chemical species *i*; u, v, and w are the components of the velocity vector in the x, y, and z directions, respectively; K_e is the eddy diffusivity used to parameterize the subscale turbulent fluxes of trace species; P_{chem} and L_{chem} are the chemical production and loss rates, respectively, due to chemical reactions; E is the source emission rate; $\left(\frac{\partial C_i}{\partial t}\right)_{\text{cloud}}$ and $\left(\frac{\partial C_i}{\partial t}\right)_{\text{dry}}$, are the rates of change of concentration due to cloud processes and dry deposition, respectively. Each term in the right-hand side of equation (1) represents the contribution of individual processes to the total concentration of each chemical species. They include horizontal advection, vertical transport, chemical reaction, emission, and dry and wet deposition.

4. Process Analysis of O_3 Formation during Different Synoptic Patterns of O_3 Episodes

The PATH model system is applied to investigate all O_3 episodes from 2000 to 2004. The performance of both MM5 and SAQM is evaluated in terms of temporal variation, spatial distribution, and statistical calculation. The details are given by Huang (2005). The results suggest good performance for meteorological predictions and acceptable performance for surface O_3 predictions.

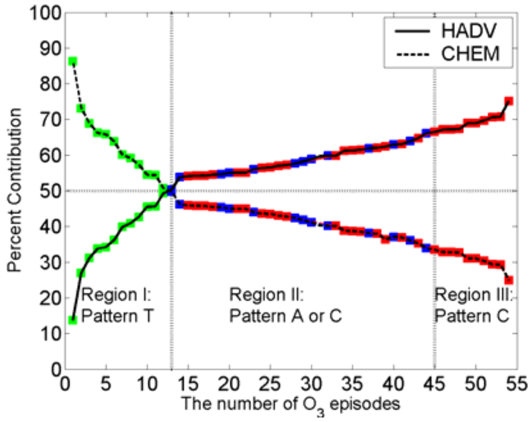


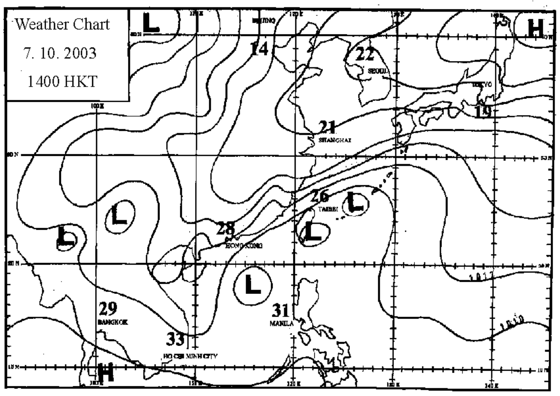
Figure 3. Percentage contributions of horizontal advection (HADV) and chemical production (CHEM) during different synoptic patterns of O_3 episodes during 2000-2004 in HK (D4).

In order to investigate the regional transport mechanism during different synoptic patterns of O_3 episodes, IPR analysis is used to calculate the relative contribution of regional transport versus local chemical production. Figure 3 shows the percentage contributions of horizontal advection versus local chemical production within the lower part of atmospheric boundary layer (0- 500 m) for all O_3 episodes during the period of 0900-500 LST when O_3 maximum production occurred. Three distinct regimes for O_3 formation mechanisms can be identified clearly as follows:

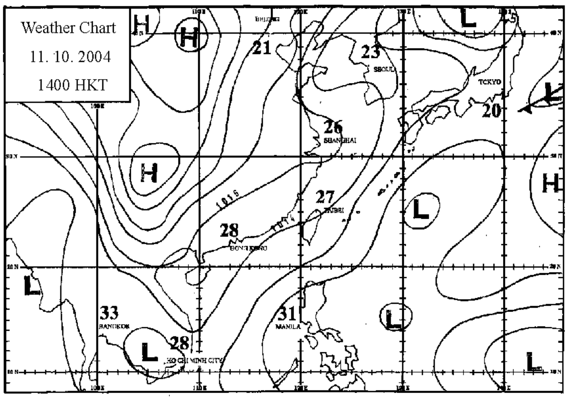
(1) Regime I is associated with twelve cases (about 22% of total O_3 episodes) during which more than 50% of total O_3 production is resulted from local chemistry production within the lower atmospheric boundary layer (ABL). Analyses of weather maps show that these cases were all associated with synoptic situations where a trough can be seen to the east of Hong Kong over the South China Sea and the Northwestern Pacific. We define this type of synoptic pattern as T (trough), and a typical example is shown in Figure 4a. IPR analyses suggest that local chemical production of O_3 in D4 (i.e., the Hong Kong domain) is more important for synoptic pattern T of O_3 episodes.

(2) Regime II is characterized by twenty two cases during which 50~65% of total O_3 production in D4 around Hong Kong is attributed to horizontal advection, i.e., regional transport. Analyses of synoptic weather maps show that this may be associated (i) with the presence of an anti-cyclone to the northeast/north/northwest of Hong Kong over mainland China (synoptic pattern "A" and an example is shown in Figure 4b), or (ii) with the presence of a tropical cyclone to the east or southeast of Hong Kong (synoptic pattern "C" and an example of which is in Figure 4c) in the South China Sea or the Northwestern Pacific. For the past five years, thirteen O_3 episode cases (24%) were found to be associated with the synoptic pattern "A" and nineteen cases (35%) were found to be associated with the synoptic pattern "C" within this regime.

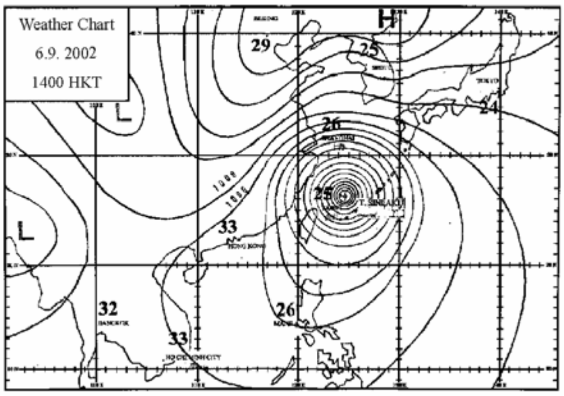
(3) Regime III is characterized by ten cases for which over 65% of O_3 production in D4 around Hong Kong is attributed to horizontal advection. Analyses of synoptic charts show that all ten cases (19% of total O_3 episodes) are associated with the presence of tropical cyclone/typhoon to the east or southeast of Hong Kong over the South China Sea or the northwestern Pacific (i.e., synoptic pattern "C"). This category of O_3 episodes are considered to be dominated by regional transport.



(a)



(b)



(c)

Figure 4. Weather charts corresponding to synoptic patterns T (7 Oct., 2003), A (11 Oct., 2004), and C (6 Sept., 2002), respectively.

There are a number of similarities in the weather conditions over Hong Kong during the three synoptic patterns ("T", "A", and "C"). First, all these cases are associated with little or no cloud cover (not shown) which is a necessary condition for the photochemical production of O_3. More importantly, background winds over Hong Kong are weak or very weak northerly winds (including also northeasterly or northwesterly) under all these situations. These conditions help to create a stable atmospheric boundary layer and strong land sea breeze circulation around Hong Kong, all of which are conducive to O_3 formation and accumulation.

However, there are also subtle differences among the three synoptic patterns, particularly in the presence of large-scale subsidence over China. When the synoptic pattern is type "C" or "A", the large-scale conditions to the north and northwest of Hong Kong are favorable to the formation of O_3. On the other hand, under synoptic pattern "T" when there is a trough to the east of Hong Kong, it is not often associated with the large-scale subsidence over much of southern China, and the conditions there may not be favorable for the formation of O_3 (although the local condition in Hong Kong may be favorable).

5. Summary and Conclusions

PATH model system is applied to simulate all 54 O_3 episodes during 2000-2004. The up-to-date high resolution land use datasets have been used to supersede those of standard MM5 over HK and PRD. Nudging technique has been applied to MM5 simulations, including analysis nudging in D1, and observation nudging in D4, respectively. The evaluations of both MM5 and SAQM simulations are performed in terms of temporal variations, spatial distributions, and statistical methods. The results suggest very good performance on meteorological predictions and reasonable performance on surface O_3 simulations.

Integrated process analysis embedded in SAQM is used to quantify the percentage contribution of regional transport versus local chemistry production during all O_3 episodes from 2000 to 2004. Three distinct regimes can be identified clearly for regional transport vs. chemistry production during all O_3 episodes. For regime I, O_3 is generated more locally, i.e., more than 50% of total O_3 production is due to local photochemical production, which is only related to synoptic pattern T cases (i.e., twelve cases). Regime II is characterized by 50~65% of total O_3 production contributing to regional transport, which is caused by synoptic pattern A or C. For region III, about 66~75% of total O_3 production can be attributed to regional transport, which is mainly associated with synoptic pattern C. The difference of regional transport is considered to be related to the scales of subsidence caused by different synoptic patterns during O_3 episodes.

In addition, the National Oceanic Atmospheric Administration (NOAA), hybrid single-particle Lagrangian integrated trajectory (HYSPLIT) model is used to identify the sources of air masses reaching Hong Kong during O_3 episodes. Trajectories show that the pathway of air masses has a significant impact on the percentage contribution of regional transport during different synoptic patterns of O_3 episodes. More details can be found in Huang et al. (2005c).

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