NUMERICAL STUDY OF OZONE EPISODE FORMATION IN HONG KONG

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ABSTRACT: A three-dimensiomal photochemical air quality model is employed to investigate an ozone episode related to typhoon activity over the South China Sea during 11-13 September 1999. An integrated process rate analysis is used to examine the relative contributions of individual physical and chemical processes in the ozone episode formation in Hong Kong. Results show that about 30% of the ozone production is due to local chemical production in the lower atmosphere boundary layer and about 70% is contributed by inter-regional transport from southern China into Hong Kong.

Key words: ozone episode, photochemical model (SAQM), process analysis.

1. INTRODUCTION

Elevated concentrations of ground level ozone are of great concern due to the deleterious impact on human health and the ecosystem [Lippmann, 1991]. Ozone is a secondary pollutant produced by a series of complicated photochemical reactions involving hydrocarbons and oxides of nitrogen ($NO_x = NO + NO_2$) in the presence of sunlight. The ozone concentrations are also influenced by transport from upwind ozone-rich air masses [Akimoto et al. 1996; Chan et al., 2000]. The superimposition of chemical production and physical processes leads to serious air pollutant events under the abundance of precursors and the favorable meteorological conditions.

Hong Kong is situated on the southeastern coast of China and adjoining the rapidly developing Pearl River Delta (PRD) of China. It is affected by a typical subtropical climate and is strongly influenced by Asian monsoon circulations and tropical cyclones originating in the Western North Pacific and the South China Sea. The Pearl River Delta (PRD) region, located in the Guangdong province, is one of the most economically dynamic region of China. Anthropogenic emissions have increased significantly in the past two decades. Inter-regional transport of airborne pollutants from the PRD region into Hong Kong is a major possible cause in the occurrence of poor air quality episodes. Ozone episodes are frequently observed when tropical cyclones are in the vicinity of the Hong Kong territory.

A series of ozone studies have been conducted extensively in Hong Kong in the past decade. Previous works are mainly focused on analyses of the ozone observation data [Wang et al., 1998; Chan et al., 2000; Lee et al, 2002]. It is not easy to obtain the inner relations among different processes and to identify which process is dominant solely by observation studies due to the limited number of measurements available. It is hoped that our limited understanding of ozone formation will be clarified and improved by using numerical simulations.

In this study, the PATH (Pollutants in the Atmosphere and Their Transport over Hong

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Kong) model is employed to investigate an ozone event related to tropical cyclones over the South China Sea and the North West Pacific. The method of process analysis is used to determine the roles of individual physical and chemical processes in the formation of the ozone episode and to identify the relative contributions to ozone concentration by local chemical production and transport from the PRD.

2. MODEL DESCRIPTION

The PATH was developed by HKEPD in 2000 for regional air quality assessment and strategic land-use and transport planning proposes. It is comprised of three main modules: a mesocale non-hydrostatic meteorological model (MM5; Grell et al. 1994); an emission processing module (EMS-95; Emigh and Wilkinson J.G., 1995); and an Eulerian transport and chemistry model (SAQM, Chang, et al. 1997).

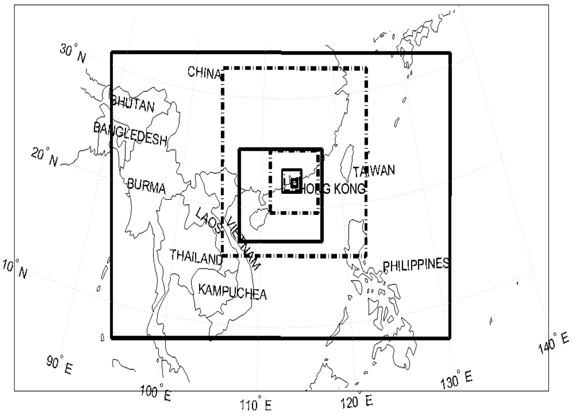

Fig.1. Settings of four nested domains in MM5 (solid line) and in SAQM (dashed line) resolutions from outmost to innermost domains are 40.5, 13.5, 4.5, 1.5 km, respectively)

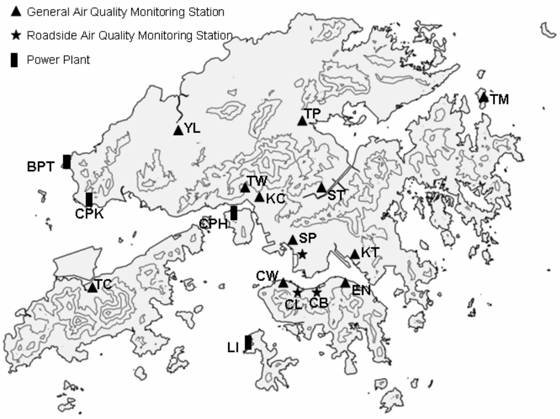

Fig.2. The topography of the Hong Kong territory, and locations of air quality stations (HKEPD) and power plants used in this study Contours are plotted every 200 m.

The MM5 model is a mesoscale meteorological model developed by PSU/NCAR. In this study, MM5 is configured with four two-way interactive nested grids (shown in Fig.1). The outmost domain (D1) covers most of southeastern China and the South China Sea to account for passages and developments of tropical cyclones, which have a significant influence on the weather of Hong Kong and vicinity. The D1 domain has 115×75 grid points with a horizontal grid distance of 40.5 km. The intermediate domains D2 and D3 contain 85×73 grid points with a horizontal resolution of 13.5 km, and 61×55 grid points with a horizontal resolution of 4.5 km, respectively. The innermost domain D4 encompasses the whole territory of Hong Kong and has 61×55 grid points with a horizontal resolution of 1.5 km. In the vertical direction, 25 sigma levels were defined unequally from the ground to the model top, with the first 10 layers in the atmosphere boundary layer for resolving the detailed structure of the atmosphere boundary layer. Four-dimensional data assimilation (FDDA) is applied to MM5 run with analysis nudging and observational nudging applied to the outermost domain and innermost domain, respectively. High resolution (as fine as 1.5km) land use data for Hong Kong and its vicinity has been developed by the HKEPD to supersede the MM5 standard land use data in an attempt to capture more accurate meteorological fields.

The US Emissions Modeling System, 1995 version (EMS-95) has been used to compile the emissions inventory for the PATH model. Emissions from four basic source categories have been estimated in the model: point sources, mobile sources, area sources, and biogenic sources. All emission data used in this study is based on base emission data established in 1997.

The air quality module in the PATH system is based on the SARMAP Air Quality Model (SAQM), modified for its application to simulate the temporal-spatial varying structure of air quality in Hong Kong. Currently, the Carbon Bond-IV chemical solver mechanism is used in SAQM. The SAQM model here also employs four nested grids with the same horizontal resolution as MM5. Each nested domain of the air quality model (SAQM) has 49×49 grid points while SAQM has 15 σ-levels in the vertical dimension with 10 levels in the planetary boundary layer where air pollutants are generally trapped.

3. CASE STUDY AND MODEL RESULTS

The 11-13 September 1999 case is one ozone episode, during which high ozone concentrations of 144.7 ppb and 141.8 ppb were observed in Tap Mun (TM) and in Tung Chung (TC) (their locations shown in Fig.2), respectively. The synoptic pattern was characterized by typhoon York occurring in the South China Sea during this period (see Fig.3a). When typhoon York is in the vicinity of Hong Kong territory, the weather was typically fine and hot over the whole territory of Hong Kong. The surface winds are dominated by weak northwesterly/westerly. All conditions were favorable for the formation of ozone event.

(a) (b)

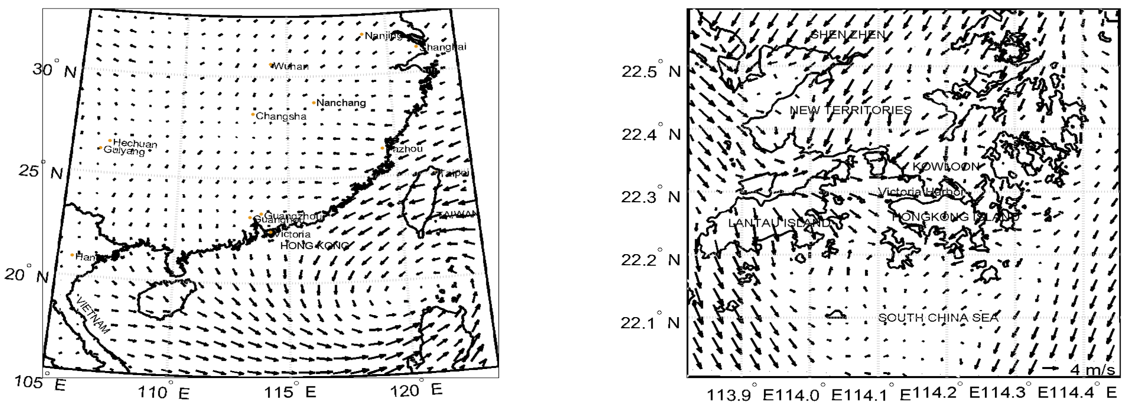

Fig.3. Simulated surface wind fields in (a) domain 1, and (b) domain 4 at 1400 LST 13 Sep 1999.

The three days period from 0200 am LST on the 11th to 0200 am LST on the 14th of September of 1999 was chosen as the simulation period for MM5. The starting time was 2 hours earlier than that of the SAQM. Initial conditions and boundary conditions were provided by 2.5 degree ECMWF (the European Center for Medium range Weather Forecasting) reanalysis data at 6 hour intervals. Hourly surface wind observations from Hong Kong Observatory stations were employed to do observational nudging in the innermost domain (D4).

The main synoptic system was captured by the MM5 simulation, as shown in Fig.3a. The simulated central position of York was very close to that of actual weather charts (not shown here). Under the influence of typhoon York, the flow patterns were dominated by northerly/northwesterly winds over the whole territory. Fig.3b presents simulated wind vectors over the Hong Kong territory at 1400 pm LST on the 13th of September. Several sea-breeze circulations were developed in Hong Kong territory.

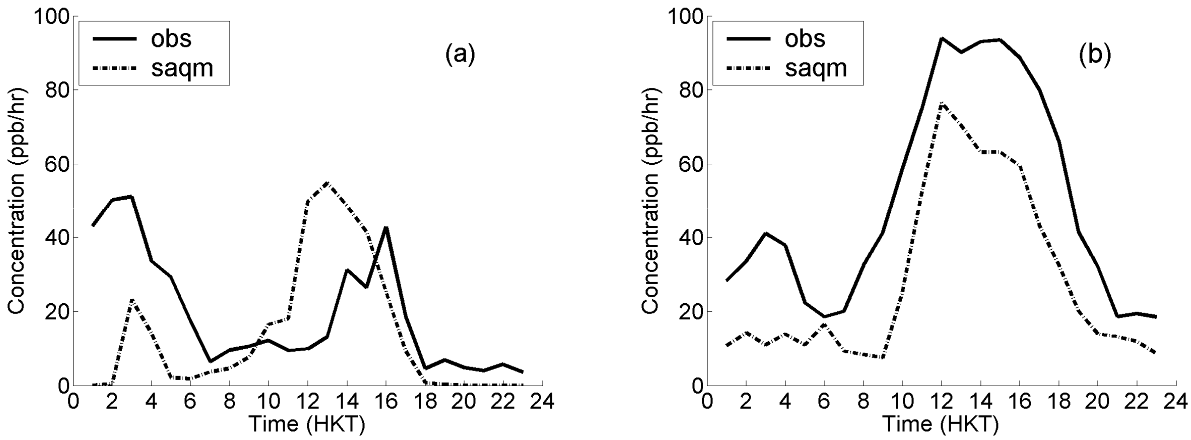

Fig.4. Comparisons of ozone concentration between observed (solid line) and simulated (dotted line) for 2 different observation stations: (a) Sham Shui Po; (b) Tap Mun.

A direct comparison between SAQM-simulated and observed hourly O_3 concentrations for the last day (the 13th of September) at two stations is presented in Fig.4 (similar comparison results for other stations, but not shown here). Tap Man (TM) station, situated in the northeast of Hong Kong territory, is a typical station in a rural area. Sham Shui Po (SP) is a typical urban station. Their locations are shown in Fig.2. Inspections of these figures reveal that the diurnal cycle of ozone is captured by the model and shows that the simulations are in good agreement with observations. Low concentrations of ozone are presented in urban area due to the titration of strong NO emissions from vehicles. Outside of the urban area, the concentrations were much higher than within the urban area.

4. PRROCESS ANALYSIS OF OZONE FORMATION

The mass continuity equations is written as the following form

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

where C_i is the chemical species concentration; u, v, w are three components of wind vector, K_e is the eddy diffusivity coefficient. The first term on the right hand side represents the horizontal advection process; the second term is the vertical transport including vertical advection and vertical diffusion (the horizontal diffusion terms are neglected); the third term $(P_{chem} - L_{chem})$ is the net change for chemical species; E denotes emission; the last two terms are wet and dry deposition term, respectively.

The 6 hours from 0900 LST to 1500 LST was selected as the period of process analyses because that was when O_3 maximum production occurred in the low atmospheric boundary layer. Each process is analyzed over the innermost domain based on the IPR (Integrated Process Rate Analysis) outputs. At 0900 LST, the ozone concentration is increasing with height and has a maximum value around 1.0 km above the ground level (expressed by the “initial” bars in Fig.5a). The shape of the ozone profile at 1500 LST has changed significantly compared with that of 0900 LST and is given by the “final” bars in Fig.5a. The maximum ozone concentration at 1500 LST occurs at about 230 m of height, which is located at the transition layer between the chimney height of power plants and ground level. The net changes of ozone concentrations are positive in the whole atmospheric boundary layer. The maximum net change rate (about 30 ppb/6hours) of ozone concentration was concentrated in the first six layers (from ground level to 230 meters above the ground level). The net change of ozone decreased gradually when the height was larger than 230m and no change (about 1.1 ppb) above 1.6 km height.

To explore the contribution of individual processes in O_3 formation, the results of process analysis on four main processes (gas-phase chemical production (CHEM), horizontal transport (HADV), vertical transport (VTRA), and dry deposition (DEPO)) leading to net change of O_3 concentration are illustrated in Fig.5b. On the ground level, the titration of NO_x with O_3 consumes about 51.81 ppb of O_3, and about 32.61 ppb of O_3 was removed by deposition. The loss of O_3 was compensated by vertical transport from upper levels and horizontal transport from outside of the territory, with contributions of 50.37 ppb and 63.45 ppb, respectively. The total change of ozone from 0900 LST to 1500 LST on the ground level was 29.4 ppb. As a result, the ground level concentration was increasing from 23.1 ppb (0900 LST) to 48.5 ppb (1500 LST).

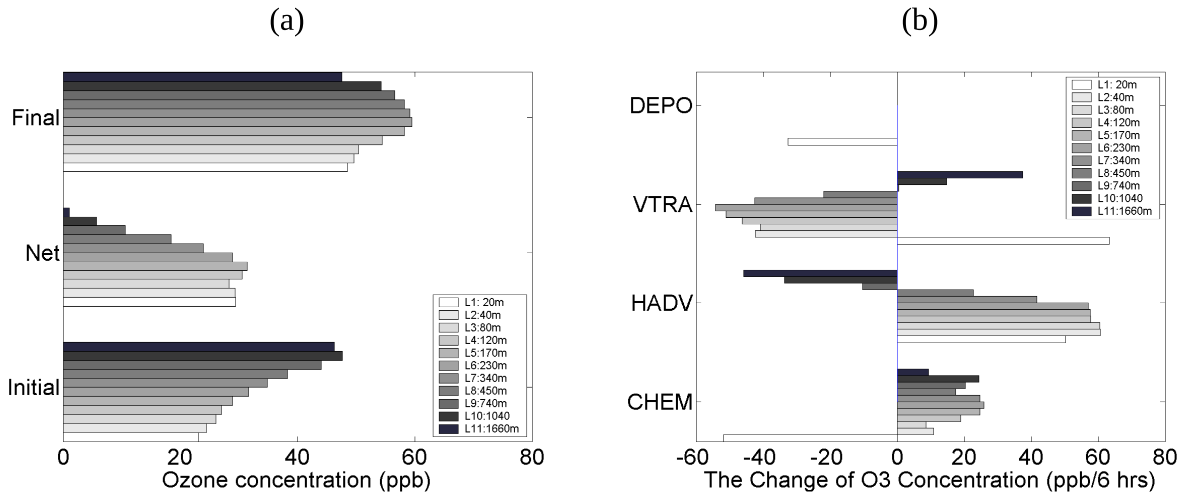

Fig.5. Relative contributions to O_3 formation by different processes from 0900 LST to 1500 LST on 13 September 1999.

O_3 was produced by photochemical reactions in the lower atmosphere (from 40 m to 1.6 km above the ground level) where the main precursors (NOx and VOC) were transported upward from surface emissions and from local power plant emissions. Meanwhile, an ozone-rich air mass was transported by horizontal advection from outside the Hong Kong region. The ozone concentrations were increased about 40~60 ppb by horizontal advection from the surface to 350m height (see HADV term in Fig.5b). By comparing the values of chemical production and horizontal transport, it was found that about 30% of the total ozone production in the lower atmosphere layer (40 m ~ 350 m height above the ground level) are produced by photochemical reaction while 70% is transported by horizontal advection from other areas.

5. CONCLUSIONS

The PATH model is applied to investigate an ozone episode related to typhoon York during 11-13 September 1999. The diurnal patterns of ozone have been reproduced by the SAQM model and are consisted with observations. The Integrated Process Rate (IPR) analysis has been employed to examine and quantify the chemical and physical processes involved in the formation of O_3 episodes. The results indicate that about 30% of the total O_3 production is due to local chemical production in the lower atmospheric layer and rest is contributed by inter-regional transport from southern China into Hong Kong.

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