REGIONAL-SCALE MODELING OZONE AIR QUALITY OVER THE CONTINENTAL SOUTH EAST ASIA

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ABSTRACT: *Long range transport of ozone and its precursors can significantly impact the air quality in downwind regions. The problem of regional transport of ozone has been studied for more than three decades in Europe and U.S but not yet in Southeast Asia. This study investigated the regional scale distribution of tropospheric ozone over the Continental South East Asia Region (CSEA) of Thailand, Burma, Cambodia, Lao and Vietnam. The Models-3 Community Multi-scale Air Quality (CMAQ) modeling system, driven by the NCAR/Penn State Fifth-Generation Mesoscale Model (MM5), is used for the purpose. The model domain covers the longitude range from 91°E to 111°E and the latitude range from 5°N to 25°N. Two most recent ozone episodes of March 24-26, 2004 and January 2-4, 2005 were selected which represent the typical meteorological conditions for high ozone concentrations periods of a year. The episode analysis was made based on available data from 10 and 4 monitoring stations located in Bangkok of Thailand and Ho Chi Minh City (HCMC) of Vietnam, respectively. The episodes were characterized with hourly ozone levels above the National Ambient Air Quality Standards of Thailand and Vietnam of 100 ppb at a number of the monitoring stations. The maximum ground level concentrations of ozone for March 2004 and January 2005 episodes reached 173 ppb and 157 ppb, respectively, in the urban plume of the Bangkok Metropolitan Region (BMR). The simulations were performed with 0.5° × 0.5° emission input data which was prepared from the regional anthropogenic emission inventory used in the Transport and Chemical Evolution over the Pacific (TRACE-P), and the biogenic emissions obtained from the Global Emissions Inventory Activity (GEIA). The simulated overall picture of ground level ozone concentrations over CSEA domain shows that the concentrations were high at the downwind areas at a considerable distance from large urban areas such as BMR and HCMC. During March 2004 episode the ozone plume moved northeastward following the Southwesterly monsoon and the maximum width of the modeled plume with the ozone above 100 ppb was about 70 km from BMR. For HCMC the ozone plume moved northward and the concentration in the city plume was lower with the width of isopleth of 50ppb of around 40 km.*

During the Jan 2005 episode the ozone plume moved southwestward following the Northeasterly monsoon and the width of the modeled plume with the ozone concentration above 100 ppb in BMR was 50 km while for HCMC the width of the 40ppb isopleth was about 30 km. The model performance was evaluated on the available observed hourly ozone concentrations. The model system was shown to be able to reproduce the peak ozone levels that occurred during the episodes at these two large urban areas, and capture the day by day variations during the selected episodes. The performance statistics MNBE, NGE, and UPA for the simulated ozone concentrations are within U.S. EPA guidance criteria and are comparable to those reported previous for other regional ozone simulations. It is shown that the MM5/CMAQ system is the suitable modeling tools for ozone prediction over the CSEA.

1. INTRODUCTION

Tropospheric ozone is a secondary pollutant mainly formed through a complex series of photochemical reactions of methane (CH_4), volatile organic compounds (VOC) and carbon monoxide (CO) with nitrogen oxides (NO_x) in the presence of sunlight. Ozone (O_3) has recently become a serious air pollution problem in many urban areas around the world. Numerous studies indicate that exposure to an elevated concentration of tropospheric ozone is a potential human health hazard (Lippmann, 1991; Weisel et al., 1995) and affects vegetation adversely. Past observations and modeling studies have shown that O_3 produced in the planetary boundary layer and its precursors are efficiently transported in the regional scale between countries and from one continent to another continent (Jacob et al, 1999). Modeling studies also suggest that the impact of long-range transport on local air quality will increase in the future (Jacob et al, 1999). The problem of regional transport of ozone has been studied for more than three decades in Europe and U.S but not yet in Southeast Asia.

Today many photochemical models are applied in different parts of the world for study on urban and regional scale air quality. Sufficient good results have been obtained in the modeling of tropospheric ozone. However, few models have been used in Southeast Asia. This paper focuses on the application of a photochemical model system for simulating ozone concentrations over the Continental South East Asia Region (CSEA) of Thailand, Burma, Cambodia, Lao and Vietnam in order to understand the current state and the transport of troposphere ozone in the tropical environment.

The primary objective of this paper is to evaluate performance of the MM5/CMAQ model system for modeling ozone concentrations on a regional scale and investigate distribution of tropospheric ozone over the Continental South East Asia Region (CSEA) through two historical ozone episodes. In this paper the CMAQ modeling results are compared with measured ozone concentrations from several monitoring stations in the study area CSEA. Analyses are conducted from the perspectives of overall performance, diurnal patterns and spatial distribution patterns.

2. DESCRIPTION OF MODEL AND INPUT DATA

2.1. The modeling system

The MM5/CMAQ modeling system was used in this study. The Model-3 Community Multi-scale Air Quality (CMAQ) version 4.3 was used to simulate the distribution of tropospheric ozone over the Continental South East Asia (CSEA). CMAQ is a Eulerian-type model developed in the U.S. Environmental Protection Agency to address tropospheric ozone, acid deposition, visibility, particulate matter and other pollutants issues in the context of "one atmosphere" perpective where complex interactions between atmospheric pollutants and regional and urban scales are confronted. The chemistry is described by the Carbon Bond Mechanism IV (CBM-IV) which includes 94 chemical reactions (Gery et at., 1989). A general description of CMAQ and its capabilities are given in Byun and Ching (1999). The Fifth-Generation Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) Mesoscale Meteorological Model (MM5) version 3.6.2 was used to generate meteorological fields for CMAQ.

2.2. CMAQ modeling domain

The CMAQ domain is defined by a 56 km (approximate 0.5°) resolution grid, based on a Mercator projection, covers the continental region of South East Asia including Thailand, Laos, Cambodia, Vietnam, and Burma. The domain consists of a 40 × 40 horizontal grid cells

and extends from 91°E to 111°E and from 5°N to 25°N. The domain has 15 vertical layers in the sigma coordinate system. Results from the surface layer (38 m) are used in this study. Initial and boundary conditions for the Model-3/CMAQ air quality simulation are not available, therefore, a three day spin-up simulation starting from clean air condition is performed prior to the episode period over the modeling domain.

2.3. Meteorological input

In this study MM5 was run in four-dimensional data assimilation mode with 30 vertical layers in the sigma coordinate system and an extended domain 2860 × 2860 km^2. The height of the first sigma layer was approximately 38 m above the ground. The meteorological fields for MM5 were obtained from the Data Support Section at the National Center for Atmospheric Research in U.S. MM5 model was run with 5 day back each episode period, 20 to 26 March 2004 and 22 to 29 January 2005. In fact, dozens of MM5 simulation were run for the selected episode periods and complete analyses of each of these MM5 simulation results are not present in this paper. The modeled wind field in Figure 2(a) and Figure 2(b) represent a typical wind patterns of the Southwest monsoon during the 24-26 March 2004 episode and the Northeast monsoon during the 2-4 January 2005 episode, respectively.

2.4. Emission data

The anthropogenic emissions of nitrogen oxides, carbon monoxide, volatile organic compounds (VOCs) and SO_2 were obtained from the regional anthropogenic emission inventory of 0.5° × 0.5° for Asia prepared by scientists at the Center for Global and Regional Environmental Research (CGRER) at the University of Iowa used in the Transport and Chemical Evolution over the Pacific (TRACE-P) (Streets et al., 2003). NO_x and hydrocarbon biogenic emissions of 1° × 1° monthly global inventory were obtained from the Global Emissions Inventory Activity (GEIA) (www.geiacenter.org) for the month of Jan and March. The biogenic emissions of 0.5° × 0.5° for the modeling domain were estimated by interpolation based on the biogenic emissions of 1° × 1°.

2.5. Ozone data

In this study, hourly surface ozone data from 10 air quality monitoring stations (Figure 1) located in BMR and 4 stations located in HCMC were collected from Pollution Control Department (PCD) in Thailand and from Department of Natural Resources and Environment (DONRE) of Ho Chi Minh City in Vietnam, respectively. Analyses presented in this paper focus on the two main urban areas in CSEA domain, Bangkok Metropolitan Region (BMR) and Ho Chi Minh City (HCMC). The CMAQ performance analyzes reported herein was limited on three subregions of Western BMR (SBMR1), Eastern BMR (SBMR2), and HCMC. For these subregions containing more than one monitoring station the maximum values between 12:00 and 16:00 LST and average concentrations for the remaining hours computed from all of the stations were used for evaluation of model performance.

Ozone concentrations exceeded the National Ambient Air Quality Standards of Thailand of 100 ppb within the subregions of SBMR1 and SBMR2 for both the selected episodes and within HCMC for January 2005 episode. The highest ozone concentration of 173 ppb was observed at station 10T in SBMR1 on 25 March 2004 and of 156 ppb was observed at station 15T in SBMR2 on 4 January 2005.

3. RESULT AND DISCUSSION

3.1. Model performance statistics

CMAQ Model performance measures for ozone were calculated by hour, and by subregion, and were reported for subregions SBMR1, SBMR2, and HCMC. The performance statistics compared modeled and observed ozone concentrations using U.S. Environment Protection Agency (1991) guidance criteria and included the mean normalized bias error (MNBE), the normalized gross error (NGE), and unpaired peak prediction accuracy (UPA). Observation-modeling pairs are excluded from the computing the statistics if the observed concentration is below a cutoff value of 40 ppb O_3. Table 2 shows the performance evaluation results of the present modeling on an hourly basis in terms of the statistical measures. Performance statistics met those recommended by the USEPA (1991).

Table 1. List of ozone monitoring stations in CSEA domain

Symbol[a]	Station Name	Source	Latitude (decimal degree)	Longitude (decimal degree)
10T	Nationnal Housing Authority	PCD	13.778	100.652
11T	Huai Khwang	PCD	13.759	100.565
12T	None-tree Vitaya	PCD	13.69	100.553
13T	Dept. of Energy Affairs	PCD	13.824	100.517
14T	Thonburi Highway District	PCD	13.598	100.355
15T	Singharatpitayakom	PCD	13.679	100.455
22T	Nonthaburi	PCD	13.910	100.500
27T	Samutsakhon	PCD	13.536	100.28
52T	Thonburi Substation,Intrapitak Road	PCD	13.741	100.482
53T	Traffic Police Residence	PCD	13.792	100.599
DO	DOSTE station	HCMC DONRE	10.7805	106.687
HB	Hong Bang Station	HCMC DONRE	10.7557	106.661
QT	Quang Trung Station	HCMC DONRE	10.8519	106.628
ZO	ZOO station	HCMC DONRE	10.7908	106.705

[a]*Same as Figure 1.*

[b]*PCD, The Thailand Pollution Department, HCMC DONRE, The Ho Chi Minh City Department of Natural Resource and Environment.*

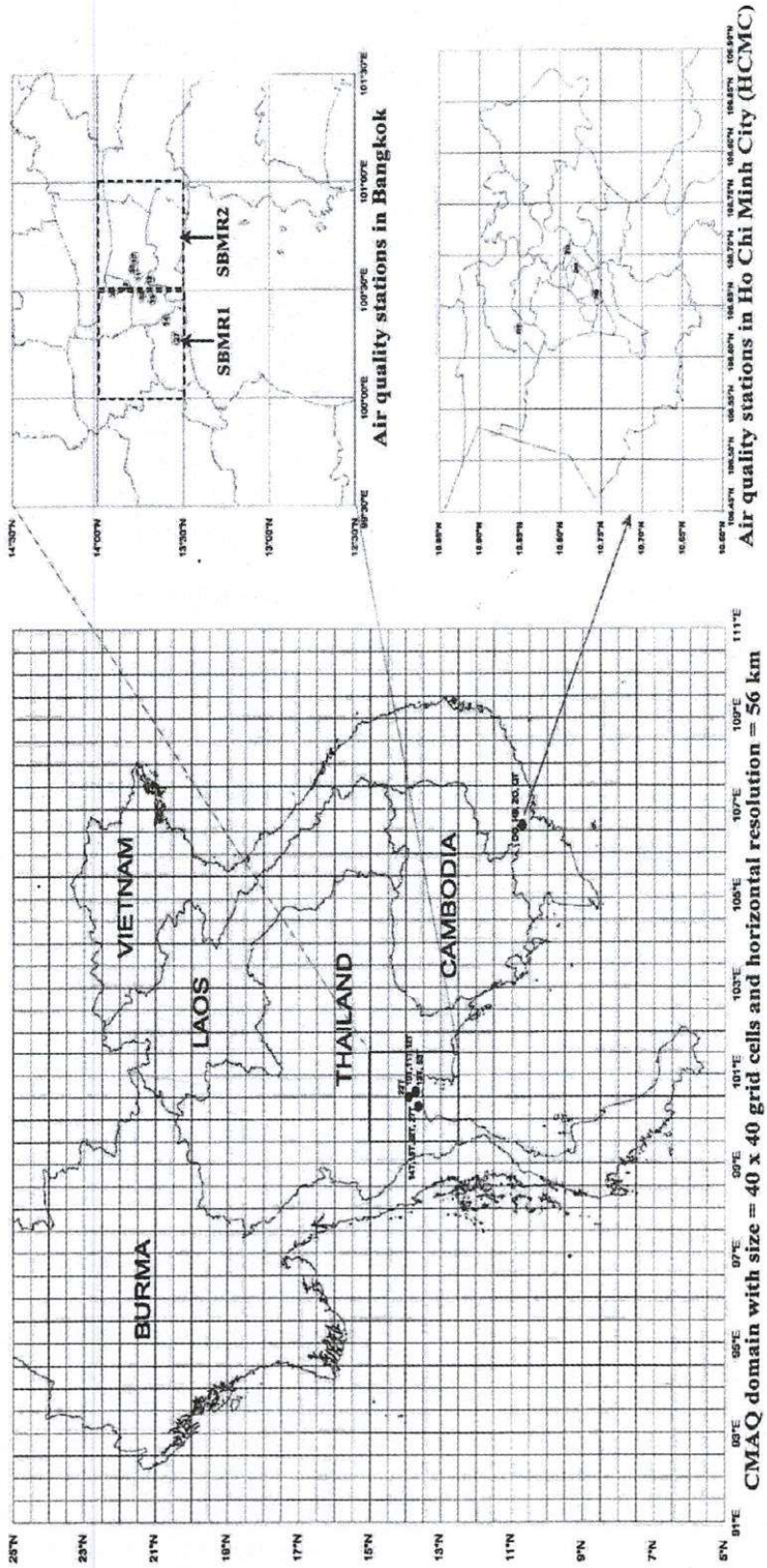
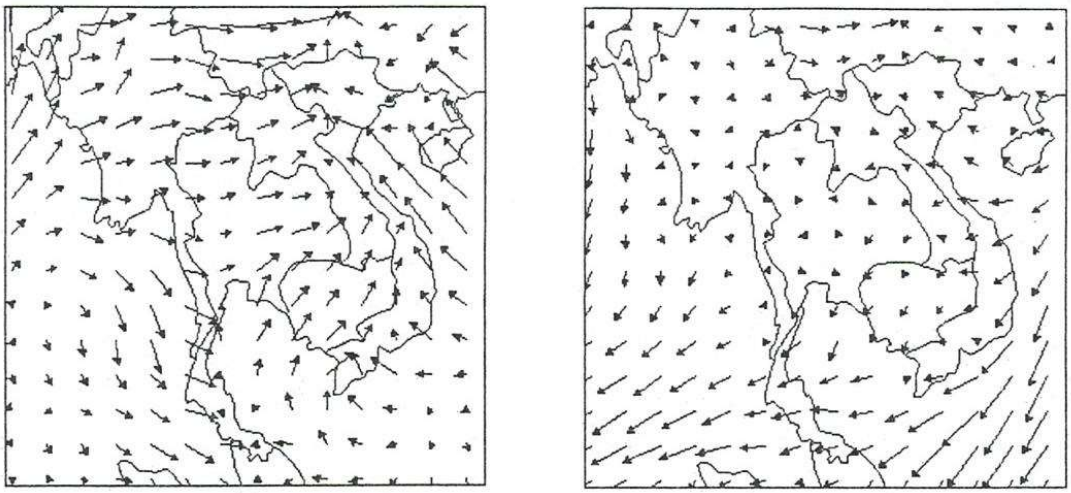


Figure 1. Model domain and location of air quality monitoring stations in CSEA domain (see also Table 1).



(a) (b)

Figure 2. Modeled surface wind fields at 6:00 UTC on (a) 24 March 2004 and (b) 3 January 2005.

Table 2. Performance statistics for 1hr O_3 concentrations

Statistics	EPA goal	24-26 March episode			2-4 January episode		
		SBMR1	SBMR2	HCMC	SBMR1	SBMR2	HCMC
n (data points)		72	72	72	72	72	72
Measured peak (ppb)		173	99	61	118	156	116
Modeled peak (ppb)		165	102	64	117	159	114
MNBE (%)	$< \pm 15$	- 8.1	-1.7	- 4.8	- 5.3	- 8.6	- 3.7
NGE (%)	< 35	9.7	19.6	13.3	18.9	23.3	25.8
UPA (%)	$< \pm 20$	- 11.6			- 13.8		

3.2. Time series and scatter plots

Figure 3 shows the time series plots for both the modeled and measured hourly ozone concentration at three subregions during the episodes. In general, the modeled results exhibited a reasonable agreement with measurements and reproduce the diurnal ozone concentration patterns very well at all subregions. The model captures the measured peaks at daytime. The plots in Figure 3(a), 3(b) show that 12:00 to 16:00 LST is the period during which ozone concentration usually exceeds 80 ppb in BMR, and peak ozone typically occurs at around 14:00 LST in the afternoon when sunlight and ambient temperature are highest in day. Figure 3(c) shows that 12:00 to 16:00 is the period during which ozone concentration usually exceeds 40 ppb in HCMC. Figure 4 further compares all 3-day hourly data from the three subregions using scatter plots, in which the diagonal line is the identity line and the other solid line is the linear regression line. Figure 4(a) and 4(b) indicate that data were clustered near the regression or identity line with $R^2 = 0.87$ and $R^2 = 0.85$ for March 2004 episode and January 2005 episode, respectively.

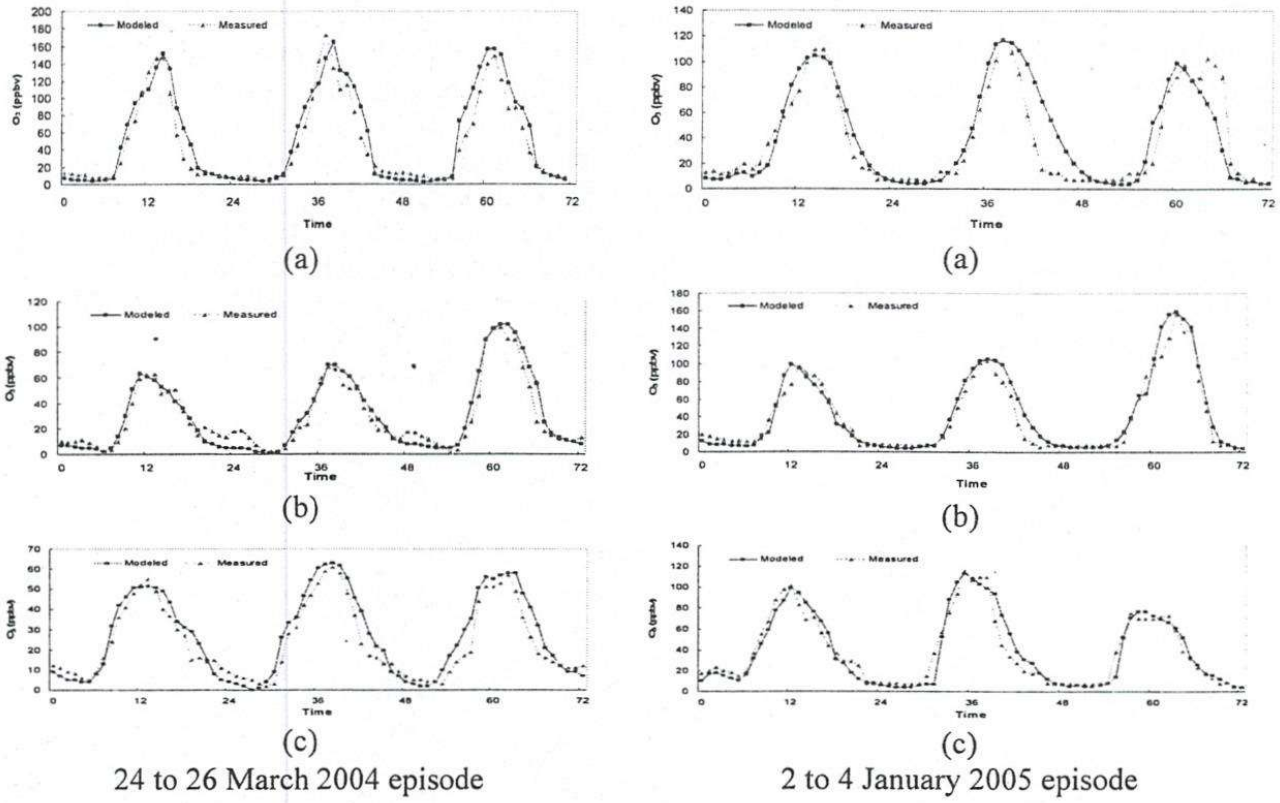


Figure 3. Comparison of hourly variation in surface O_3 modeled concentrations with measurements at (a) SBMR1, (b) SBMB2 and (c) HCMC

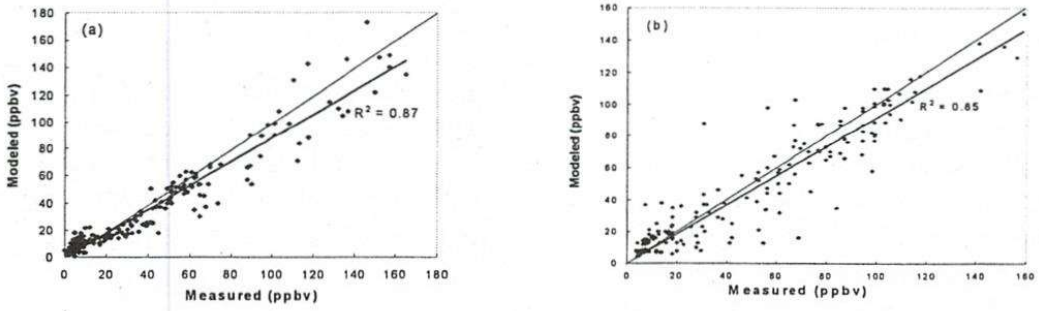
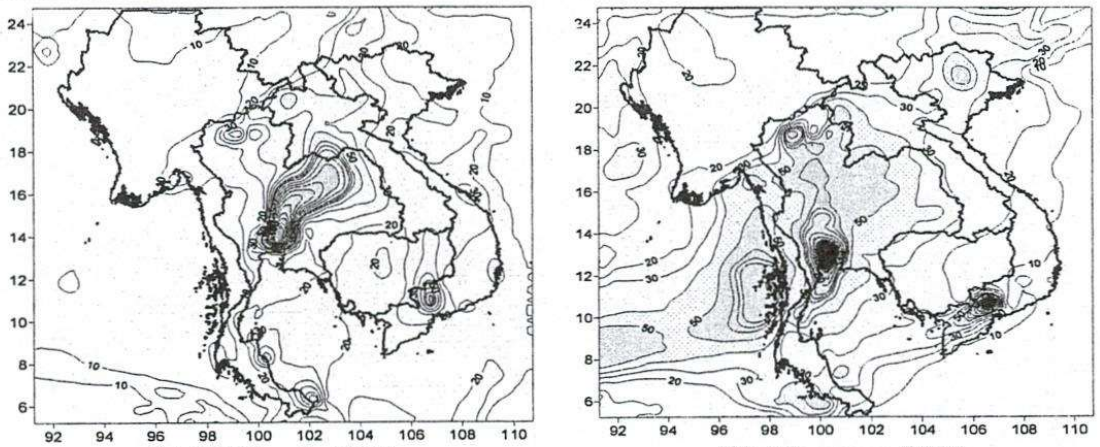


Figure 4. Scatter plots of measured ozone concentrations vs. modeled values at all three subregions SBMR1, SBMR2, and HCMC for (a) 24-26 March 2004 episode and (b) 2-4 January 2005 episode.

3.3. Spatial distributions of ozone over CSEA

The spatial distributions of O_3 concentrations at surface level (lowest layer) over CSEA domain at 14:00 LST of episodic days are shown in Figure 5. The main cities of the domain such as Bangkok Metropolitan region and Ho Chi Minh City, generally show high O_3 concentrations mainly due to primary anthropogenic emissions. Highest O_3 concentrations are centered over Bangkok Metropolitan and its surrounding areas. The concentration patterns show that there are a potential advection and transport of the ozone and its precursors from the major urban centres (BMR and HCMC) to some downwind areas. In March 2004 episode (Figure 5(a)), elevated ozone concentrations are found in the northeastern BMR and the north of HCMC in association with Southwest monsoon (SW) and Southerly winds. During March

2004 episode the ozone plume moved northeastward following the Southwesterly monsoon and the maximum width of the modeled plume with the ozone above 100 ppb was about 70 km from BMR. For HCMC the ozone plume moved northward and the concentration in the city plume was lower with the width of isopleth of 40ppb of around 40 km. During the Jan 2005 episode the ozone plume moved southwestward following the Northeasterly monsoon (Figure 5(b)), elevated ozone concentrations are found in the southwestern BMR and the southwest of HCMC. The width of the modeled plume with the ozone concentration above 100 ppb in BMR was 50 km while for HCMC the width of the 50ppb isopleth was about 30 km. This implies that long-range transport may cause elevated concentrations in remote area downwind of polluted regions.



(a) 26 March, 2004 (b) 4 January, 2005

Figure 5. Modeled surface ozone distributions over CSEA domain at 7:00 UTC

4. CONCLUSION

The Models-3 CMAQ modeling system with meteorological fields provided by MM5 was applied to investigate two O_3 episodes over the CSEA. Overall, the model performed reasonably well in modeling O_3 concentrations over the modeling domain and the episodic period. The model simulated very well the diurnal variation and daily peak O_3 concentrations. Spatially, the model provides overall picture of ground level ozone concentrations over CSEA domain which shows the concentrations were high at the downwind areas at a considerable distance from large urban areas such as BMR and HCMC.

MÔ HÌNH HÓA CHẤT LƯỢNG KHÔNG KHÍ NỒNG ĐỘ ÔZÔN MẶT ĐẤT CHO KHU VỰC LỤC ĐỊA ĐÔNG NAM Á

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TÓM TẮT: *Khuếch tán trên phạm vi rộng của ôzôn mặt đất và tiền chất của nó có thể ảnh hưởng nghiêm trọng đến chất lượng không khí của các khu vực tiếp nhận dưới hướng gió. Vấn đề vận chuyển chất ô nhiễm ôzôn xuyên vùng đã được nghiên cứu cách đây hơn 3 thập kỷ ở Châu Âu và Hoa Kỳ nhưng chưa được nghiên cứu ở khu vực Đông Nam Á. Bài báo này trình bày kết quả nghiên cứu áp dụng công cụ mô hình xác định sự phân bố ôzôn cho khu vực lục địa Đông Nam Á (CSEA) bao gồm Thái Lan, Miến Điện, Campuchia, Lào và Việt Nam. Hệ thống mô hình chất lượng không khí CMAQ – MM5 được sử dụng trong nghiên cứu này. Khu vực mô hình hóatrải dài từ kinh độ 91° Đông đến 111° Đông và từ vĩ độ 5° Bắc đến 25° Bắc. Hai kịch bản ô nhiễm ô zôn nồng độ cao từ 24 đến 26 tháng 3 năm 2004 và từ 2 đến 5 tháng 1 năm 2005 xảy ra trong điều kiện khí tượng điển hình của khu vực Đông Nam Á được lựa chọn để mô hình hóa. Các kịch bản này được phân tích và lựa chọn trên cơ sở số liệu quan trắc chất lượng không khí từ 10 trạm ở Băng Cốc, Thái Lan và 4 trạm ở thành phố Hồ Chí Minh, Việt Nam. Các kịch bản lựa chọn trong nghiên cứu nghiên cứu này có nồng độ ô zôn trung bình giờ ở các trạm quan trắc vượt quá giá trị cho phép 100 ppb của tiêu chuẩn chất lượng không khí xung quanh của Thái Lan và Việt Nam. Nồng độ ôzôn mặt đất lớn nhất cho kịch bản tháng 3 năm 2004 là 173 ppb và cho kịch bản tháng 1 năm 2005 là 157 ppb. Hệ thống mô hình được thực hiện với dữ liệu phát thải 0.5° × 0.5° thu thập từTrung Tâm Nghiên Cứu Môi Trường Vùng và Toàn Cầu (CGRER) của Đại Học Iowa. Kết quả mô hình minh họa trong bản đồ ô nhiễm ôzôn mặt đất cho thấy nồng độ ôzôn cao tại các khu vực dưới hướng gió của các thành phố lớn như Băng Cốc và thành phố Hồ Chí Minh. Trong kịch bản tháng 3 năm 2004 vệt khói khuếch tán ôzôn di chuyển theo hướng Đông Bắc do ảnh hưởng của gió mùa Tây Nam và chiều rộng của vệt khói với nồng độ ôzôn lớn hơn 100 ppb là 70 km cho khu vực Băng Cốc. Đối với thành phố Hồ Chí Minh vệt khói khuếch tán ôzôn di chuyển theo hướng Bắc và chiều rộng của vệt khói với nồng độ ôzôn lớn hơn 50 ppb là 40 km.*

Trong kịch bản tháng 1 năm 2005 vệt khói khuếch tán ôzôn di chuyển theo hướng Tây Nam do ảnh hưởng của gió mùa Đông Bắc và chiều rộng của vệt khói với nồng độ ôzôn lớn hơn 100 ppb là 50 km cho khu vực Băng Cốc, trong khi đó đối với thành phố Hồ Chí Minh vệt khói khuếch tán với nồng độ ôzôn lớn hơn 50 ppb có chiều rộng là 30 km.

Kết quả mô phỏng của mô hình được so sánh, đánh giá với các số liệu ôzôn đo đạc được tại các trạm quan trắc. đánh giá này cho thấy hệ thống mô hình có thể mô phỏng các nồng độ ô zôn cực đại xảy ra trong các kịch bản trên cũng như mô phỏng được tiến trình dao động nồng độ ôzôn trong những ngày của kịch bản lựa chọn. Các chỉ số thống kê đánh giá kết quả mô hình như MNBE, NGE, và UPA nằm trong giới hạn cho phép theo hướng dẫn của USEPA và phù hợp với các nghiên cứu khác cho các khu vực khác nhau trên thế giới. Điều này chứng tỏ rằng hệ thống mô hình MM5-CMAQ là công cụ thích hợp cho việc mô hình hóa ôzôn mặt đất cho khu vực Đông Nam Á.

Key words: *ozone, CMAQ – MM5, Bangkok, HCMC,* SOUTH EAST ASIA

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