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APPLICATION OF WRF-CMAQ MODELING SYSTEM TO STUDY OF URBAN AND REGIONAL AIR POLLUTION IN BANGLADESH

M. A. Muntaseer Billah Ibn Azkar*, Satoru Chatani and Kengo Sudo
Department of Earth and Environmental Science, Graduate School of Environmental Studies
Nagoya University, Furo-Cho, Chikusa-Ku, Nagoya, Japan

1. INTRODUCTION

The rapid economic development that is being taken place in developing countries during recent years has lead to severe deterioration of their local as well as regional air quality. The case of Bangladesh is not different from other developing country. Particularly Dhaka, the capital of Bangladesh, is facing a high level of air pollution. Emissions from various kinds of diesel vehicles and badly maintained automobiles, biomass/coal burning for cooking and in the brick kilns, huge number of construction works, re-suspended road dust are the main sources of air pollution in Dhaka (Bilkis et. al, 2005). Additionally, emission from outside of Bangladesh may also be a significant contributor for the worsening of local air quality in Bangladesh. A coupled WRF-CMAQ air quality modeling system was applied to predict the ambient concentrations of NO2, CO, SO2, O3, and PM2.5 in the Dhaka City as well as whole Bangladesh. Moreover, the modeling system was used to investigate whether there is any pollution contribution from outside Bangladesh. A severely polluted month January 2004 has been simulated and model performance has been evaluated with observations including satellite data. Our WRF-CMAQ modeling system reproduced the general trends of air pollutants, but underestimated the peak magnitudes of pollutants significantly. This paper discusses the model performance and reasons for these discrepancies in terms of the various input data including emissions and meteorological parameters. The contributions of transbounadry pollution were also quantified in this study.

2. MODELING APPROACH:

The modeling system of this study consists of a meteorological model, an air quality model and an emission inventory database and all these modeling tools were integrated into a general framework to simulate the local and regional atmospheric circulation and predict the pollutant concentrations in Dhaka City. Details of each component are described in following subsections.

2.1 Meteorological Model:

The meteorological model selected in this study to provide the meteorological fields required for chemical-transport model and the emission processing system was the Weather Research and Forecasting (WRF) modeling system version 3.1 (Skamarock and Klemp, 2008).

2.2 Air Quality Model:

The Community Multiscale Air Quality Model (CMAQ) (Byun and Ching, 1999) has been widely applied to various air quality issues all over the world (Sokhi et al., 2006; Chen et al., 2007). In this study CMAQ version 4.7 was used to simulate local and regional air quality of Bangladesh.

2.3 Domain and Model Setup:

The modeling domains in this study for both WRF and CMAQ models are shown in Fig. 1. The coarse domain (D1) extends from 6°N to 40°N and 70°E to 110°E. D1 has the size of almost 3600 km × 3600 km, centered at 23.5°N, 90.5°E and covers almost whole South Asian region. Coarse domain (D1) was set in such a way that intended to capture synoptic features and general circulation patterns so that the transboundary transport of pollutants to Bangladesh from its surrounding area can be taken into account. The nested domain (D2) comprises the whole Bangladesh and its nearest surrounding area. The horizontal grid spacing of D1 and D2 were set as 45 km and 15 km respectively. D1 and D2 consist of 81×81 and 79×79 horizontal grids respectively and both domains have 27 vertical layers. The horizontal coordinate is based on the Lambert conformal projection for both models with vertical coordinate based on the sigma-p coordinate. The Four Dimensional Data Assimilation (FDDA) grid nudging was applied to temperature, specific humidity and wind components with a nudging co-efficient of 1.0×10^{-4} for all parameters.

**Corresponding author:* M. A. Muntaseer Billah Ibn Azkar, Department of Earth and Environmental Science, Graduate School of Environmental Studies, Nagoya University, Nagoya, Japan; e-mail: anirban_9992002@yahoo.com.

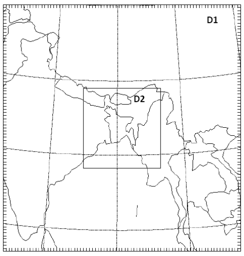

Fig. 1. Modeling domains for the application of WRF and CMAQ.

The WRF simulations were driven by the National Center for Environmental Prediction (NCEP) re-analysis data with 1°×1° spatial resolution and 6h temporal resolution to generate the required initial and boundary conditions. The WRF output files were processed with the Meteorology-Chemistry Interface Processor (MCIP) version 3.4 which create the required meteorological input data to run CMAQ. The Statewide Air Pollution Research Center mechanism (SAPRC99) was used as chemical mechanism for CMAQ simulation. The CAMQ default values were used for initial conditions (ICONs) for both domains and boundary conditions (BCONs) for coarse domain (D1). BCONs for nested domain (D2) were generated from D1 results.

2.4 Episode Selection:

In this study, December 2003 simulation was regarded as model spin up and January 2004 simulation was used for analysis. This month-long episode was chosen for the simulations to represent a typical peak pollution episode in Dhaka City.

2.5 *Emission Database*:

The Frontier Research Center for Global Change (FRCGC) has developed an emission inventory named REAS (Regional Emission inventory in Asia) including key air pollutants with the resolution of 0.5°×0.5° for the whole Asian continent in order to understand the role of trace constitutes in the atmosphere (Ohara, 2007). The REAS emission inventory data were used in this study as emission input for the CMAQ model.

3. RESULTS & DISCUSSIONS:

3.1 Evaluation of CMAQ Results:

Observed air quality data are hardly available in Bangladesh to evaluate the performance of CMAQ model. The capital Dhaka has only one Continuous Air Monitoring Station (CAMS) which has been collecting air quality data since April 2002 with several discontinuities due to the malfunctioning of different instrument. Hourly measurement of NO2, SO2, CO, O3 and 24-hour measurement of PM2.5 are available at this CAMS from April 2002. This is the only air quality database in Bangladesh that had to be used to evaluate the CMAQ performance in this study. Air quality data for other places outside Dhaka in Bangladesh are not available at all. Although it may not be fair to evaluate modeled data by comparing with only one station data, it can at least give an idea about the tendency of CMAQ model in this region. This evaluation can also be used to assess the performance of CMAQ model, required

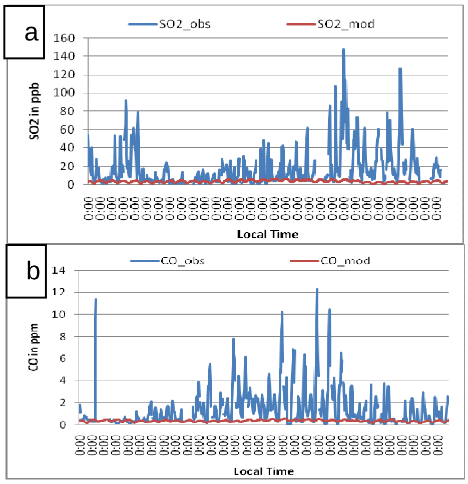

Fig. 2. Time series of the observed and simulated SO_2 (a), and CO (b) in Dhaka during January 2004.

improvement of its input parameter, and its future applicability to this region. Fig. 2 and 3 show the time series comparison between observed and modeled gaseous pollutants and PM2.5 in Dhaka, respectively. It can be seen that every pollutant was largely underestimated by CMAQ. In case of gaseous pollutants, it is almost impossible to make any comment regarding CMAQ performance in Bangladesh on the basis of these time series plot as the amount of underestimations are several times. The model was also not able to capture the hourly peak of any of gaseous pollutants. We assume that the large underestimation is due to the emission input of CMAQ model. The REAS emission inventory database was used as emission input in this simulation and the horizontal resolution of this emission database (50km) was much lower than CMAQ grid resolution (15km) which can be a reason for this large underestimation. Moreover, temporal and seasonal variations of emission from different sources were not considered in the REAS emission inventory. That means the same amount of emission was estimated throughout in a specific year in REAS emission inventory. Seasonal variation of emission is important for Dhaka City as well as whole Bangladesh. Such example is,- operation of brick kilns which has been identified one of the important sources of air pollution in Bangladesh. As brick is the main construction material in Bangladesh, a huge number of brickfields (more than 4000 in Bangladesh and 500 in Dhaka city), those use substandard fuels such as high sulfur coal, tires and wood energy, only operate during winter months (November to March) due to favorable dry meteorological conditions. Moreover, biomass burning in rural area as well as slum area of big cities also increases during winter in Bangladesh. So real time emission information was required in order to simulate the hourly concentration of air pollutants. The lack of this time specific emission information may be another important cause of underestimation. Open biomass burning is a significant source of various air pollutants in India and Bangladesh, but not included in REAS emission inventory which may also be a reason of underestimation. Furthermore, several high peaks of gaseous pollutants in observed data may be owing to very local and time specific emission sources. Consequently, these high peaks cannot be reproduced by CMAQ without using real time emission input. Additionally, erroneous measurement of these gas analyzers may also have some contribution to this underestimation. The scenario (Fig. 3.) is much better in case of PM2.5. Though CMAQ underestimated 24-hour average PM2.5 concentration, it captured the trend of daily variation.

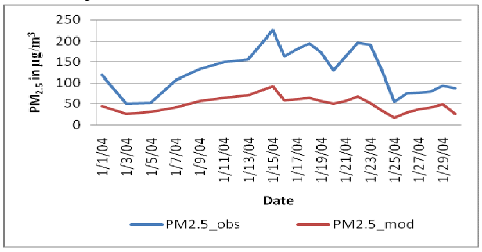

Fig. 3. 24-hour average observed and simulated PM2.5 in Dhaka during January 2004.

3.2 Comparison with Satellite Observation:

Due to the huge underestimation by CMAQ in comparison with time series observed data, we were interested to compare the CMAQ result with available satellite observation. Tropospheric NO2 column from SCIAMACHY was used in this comparison. In order to compare with satellite column data, CMAQ result of January 2004 was also converted to column data. Fig. 4. compares

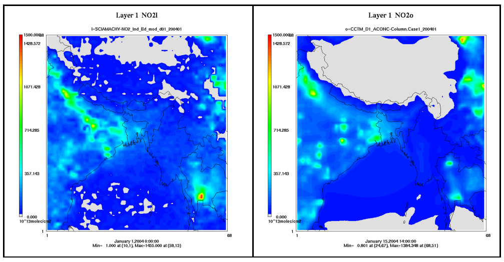

Fig. 4. Spatial distributions of tropospheric NO2 column in D1 during January 2004. SCIAMACHY (left) and CMAQ (right).

spatial distributions of SCIAMACHY satellite observation and CMAQ simulation result NO2 in January 2004. It can be seen that the distribution is well reproduced in India but the simulation fails to reproduce a high concentration spot in Bangladesh which can be found slightly in the satellite image.

3.3 CMAQ Sensitivity Analysis:

Some sensitivity analyses with WRF-CMAQ modeling system were performed in this study in order to check its applicability in Bangladesh. Total of six simulation cases including base case (Case-1) shown in Table 1 were conducted and all of these cases were related to emission sensitivity of CMAQ model. Contributions of emission inside Bangladesh and outside Bangladesh were also examined through these sensitivity studies.

Table.1 Simulation cases for WRF-CMAQ sensitivity analysis

Case	**Emission sensitivity**
Case-1	Original REAS emission
Case-2	Shut-off emission in Region-1 (Inside Bangladesh)
Case-3	5-times increase of emission in Region-1 (Inside Bangladesh)
Case-4	Shut-off emission in Region-2 (West Bengal)
Case-5	Shut-off emission in Region-3 (North India)
Case-6	Shut-off emission in Region-2 (West Bengal) and Region-3 (North India)

In order to carry out these sensitivity analyses, three specific potential emission source regions were identified. Emissions inside Bangladesh, West Bengal area of India, and North India were selected as source Region-1, Region-2, and Region-3 respectively. Case-1 was the base case using original REAS emission inventory and have already discussed the results of this case in previous section. Emissions inside Bangladesh (Region-1) were shut-off and increased 5-times of

REAS emission in Case-2 and -3 respectively to check the response of CMAQ. Emissions in West Bengal (Region-2) and North India (Region-3) were shut-down in Case-4 and -5 to quantify the contribution of these two source regions. Moreover, Case-6 was conducted by shutting off emissions in Region-2 and -3 at the same time to quantify the combined contribution from outside Bangladesh. Fig. 5 shows some results of Case-2 simulation where emissions were totally shut down in Region-1 i.e., in Bangladesh. In spite of zero emission in Bangladesh, a significant amount of pollution was found inside the country which can be considered as background concentration.

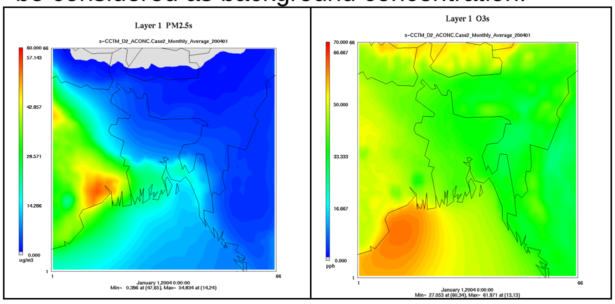

Fig. 5. Background concentration of PM2.5 (left), and O3 (right) in Bangladesh (Case-2, Domain-2).

Approximately 20-40 μg/m^3 background PM2.5 was found and again south western part were more impacted than rest of the country. In the case of O3, the background concentration was almost homogenous throughout the country with magnitude of 45 ppb. It can be assumed from this figure that Bangladesh may be significantly influenced by transboundary transport of pollution, particularly for PM2.5. However, south western part may be more influenced by this transportation compared to the rest of the country.

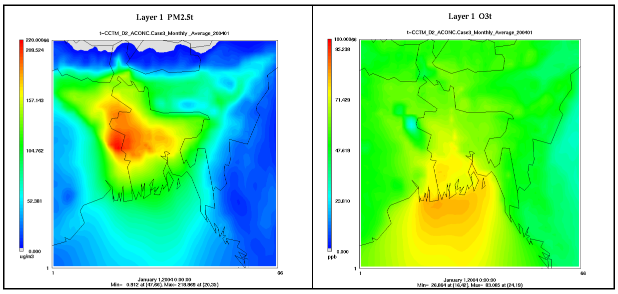

Fig. 6. CMAQ's result from Case-3 with 5-times increase of REAS emission in domain-1.

Since CMAQ largely underestimated the concentrations of all pollutants in Case-1 simulation and it seemed that these discrepancies were mainly due to the emission input, we increased REAS emission inside Bangladesh by 5-times to see the response of CMAQ in Case-3 simulation. Fig. 6 shows the emission sensitivity of CMAQ in domain-1. Significant increases of simulated concentration were found in both domains due to increase of REAS emission. Fig. 7 shows the time series plot of observed and simulated (Case-3) concentrations of CO, and PM2.5. It can be seen that though CO concentrations were increased, but still the model cannot reproduce the night time peaks. Moreover, daytime concentrations of CO were overestimated. On the other hand, PM2.5 was overestimated due to the increase of REAS emission. However, it is clear from this comparison that discrepancies were largely dependent on emission input of CMAQ model.

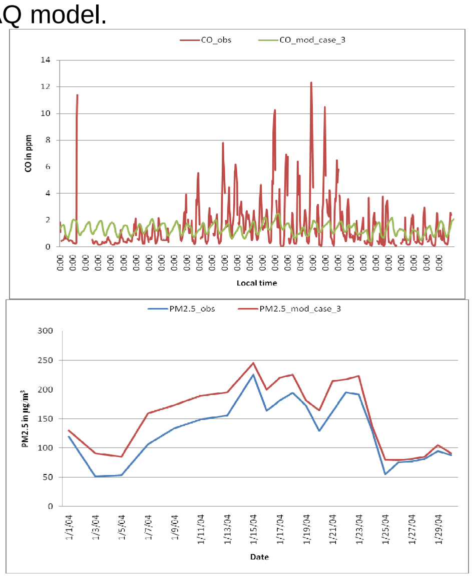

Fig. 7. Time series of observed and simulated (Case-3) CO and PM2.5 concentrations in Dhaka.

As CMAQ was found significantly sensitive to its emission input in this study, we were intended to identify some regional emission sources which have significant contribution to pollution inside Bangladesh. In Case-4 simulation, emissions of West Bengal area (Region-2) were shut-off and the impacts of transport from this region on Bangladesh were investigated. Significant reduction of pollution, particularly in PM2.5 and O3, was simulated inside Bangladesh due to shutting-off of emission in West Bengal. Similar approach was applied while simulating Case-5 by shutting down the emissions in North India (Region-3). It is interesting to see which source region is more significant for Bangladesh. In order to investigate the relative importance of both source regions, contribution of each region to Bangladesh was quantified in percentage. It was found that West Bengal area (Region-2) had relatively higher contribution than North India (Region-3).

Fig. 8 shows the horizontal distribution of percentage differences between Case-1 and Case-2, -4, -5, -6 simulations for PM2.5 (left column) and O3 (right column). These pictures represent the contribution of each region to Bangladesh. The difference between Case-1 and

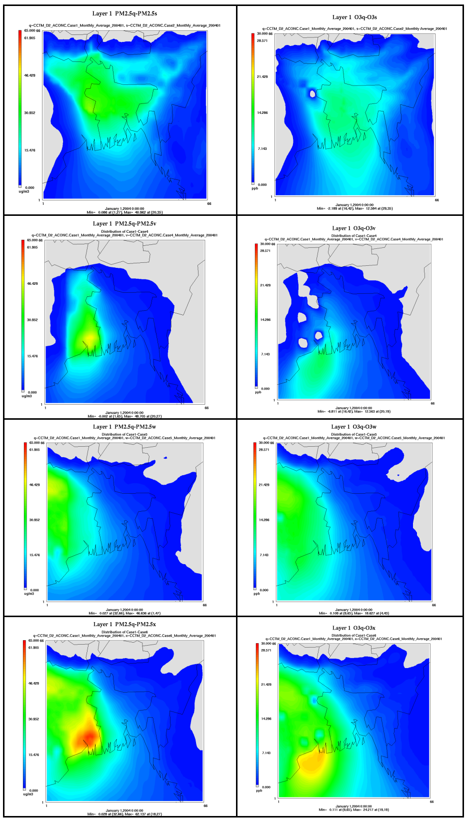

Fig. 8. Horizontal distribution of percentage differences between Case-1 and -2, -4, -5, -6 for PM2.5 (left column) and O3 (right column) in D2.

Case-2 represents the contribution of Region-1 emission i.e., emission inside Bangladesh. The difference between Case-1 and Case-4 represents the contribution of Region-2 emission i.e., emission in West Bengal. Similarly, difference between Case-1 and Case-5 shows the contribution of Region-3 i.e., emission in North India. An additional simulation was performed by shutting off emission in both Region-2 and Region-3 at the same time in Case-6. The difference between Case-1 and Case-6 shows the maximum transboundary impact inside Bangladesh due to emission of West Bengal plus North India. PM2.5 appeared to be more transported among all pollutants. The contributions from both the region were not homogeneous throughout the country. Western part of Bangladesh, particularly south-west region is more influenced by transboundary transport of pollutants from India. This may be due to the adjacent Kolkata city which is considered as one of the densely populated and polluted metropolitan area in India.

Relative and accumulated contribution in monthly average CO, O3, and PM2.5 were estimated from CMAQ results of Case-6 simulation and summarized in Table 2. On average, 11% CO from West Bengal and 10% CO from North India are transported to Bangladesh. In the western part of Bangladesh, this contribution may reach up to 34% and 18% respectively. O3 concentration was relatively less influenced by transboundary transport. Average 7% from West Bengal and 8% from North India may contribute to the ground level concentration of O3 in Bangladesh. However, O3 transport from both regions can be higher in the south western part of Bangladesh. Concentration of PM2.5 in Bangladesh may be more influenced by regional transport compared to CO and O3. Again West Bengal can supply on average 18% with maximum 43% PM2.5 which is higher than North Indian contribution.

Table. 2 Estimated transboundary contributions in Bangladesh from India.

Pollt.	Contribution in %					
	Region-2 (West Bengal)		Region-3 (North India)		Region-2 + Region-3	
	Avg.	Max.	Avg.	Max.	Avg.	Max.
CO	11	34	10	18	21	53
O3	7	16	8	15	15	31
PM2.5	18	43	19	28	35	67

While summing up the contribution from both regions, the figures are quite significant. Almost 21% CO, 15% O3, and 35% PM2.5 in Bangladesh can be transported from outside the country. This can be explained as in January and whole winter season, a center of high pressure lies over the northwestern part of India. A stream of cold air flows eastward from this high pressure and enters Bangladesh through its northwest corner by changing its course clockwise, almost right angle. This wind is the part of the South Asian winter monsoon. During this season, wind inside the country generally has a northerly component (flowing from north or northwest). This north, northwesterly wind coming from heavily polluted Indian region to the Bay of Bengal through Bangladesh may transport the significant amount of pollution to the country. Since this transboundary transport of pollutants to Bangladesh was simulated to be quite significant as revealed in Table.2, more investigations are required to reach conclusion. One important point is that REAS emission inventory was used in this study as emission input of CMAQ and it was largely underestimated the concentration of all pollutants. From this point of view, the transbaoundary contribution could be higher than our simulation if realistic emission information could be provided for whole study area. Nevertheless, only one observation point is not enough to evaluate the performance of CMAQ. It is prioritized to check the validity of CMAQ prediction before going to quantify the exact contribution of transboundary transport of air pollution.

4. CONCLUSION:

This is the first attempt to apply WRF-CMAQ modeling system to simulate the concentration of different pollutants in Bangladesh. A number of sensitivity analyses were conducted in this study to check the performance of CMAQ in this region. Transboundary transport of pollution in Bangladesh was also quantified through these simulations. The following conclusions are summarized for future directions of the study:

- The comparison between simulated and observed temperature and wind fields showed that the WRF succeeds in generation of meteorological inputs to run CMAQ model for this region.
- The comparison of observed and simulated concentrations of different air pollutants showed that concentrations were largely underestimated by CMAQ. These discrepancies were heavily dependent on emission input of CMAQ model.
- Emission sensitivity of CMAQ model was tested. Our model response suggests underestimation of REAS emission for this region. Realistic high resolution emission information is required to reproduce the peak magnitudes of pollutant's concentrations.
- Significant contributions of transboundary transport of pollution were found inside Bangladesh. More evaluations of CMAQ performance are required to confirm these contributions.

Overall, the methodology of coupling a mesoscale meteorological model (WRF) with a three dimensional air quality model (CMAQ) for simulating pollutant concentrations in this region has shown more or less encouraging results. However, improvement in the emission inventory inputs and more detailed sensitivity analysis with CMAQ model will be required to conclude on the reliability and applicability of WRF-CMAQ modeling system in this region, and these will be conducted in future work.

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