## FUTURE PROJECTION OF SURFACE OZONE IN EAST ASIA WITH CMAQ and REAS INVENTORY

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### 1. INTRODUCTION

Tropospheric ozone ($O_3$) plays a central role in controlling oxidizing capacity through generation of hydroxyl radicals (OH). As a major greenhouse gas, it is estimated to have made the third largest contribution to increases in direct radiative forcing since the pre-industrial era. Furthermore, tropospheric $O_3$ is most important air pollutant, which can cause damage to human health, agricultural crops, and natural ecosystems.

Recently it was reported that tropospheric $O_3$ levels observed over Japan have been rising over the last three decades, likely as a consequence of increasing emissions of nitrogen oxides (NOx) from Asia (*Naja and Akimoto*, 2004). Emissions from Asia also have a potential impact on air quality over the United States, and on widespread $O_3$ pollution in the Northern Hemisphere through intercontinental transport (*Wild and Akimoto*, 2001). The $O_3$ levels will be enhanced in future, particularly over Asia where NOx emissions are estimated to increase most severely (*Akimoto*, 2003; *Ohara et al.*, 2006).

In the present study we report the results of future projection of surface ozone over East Asia using by the CMAQ model and new developed Asian emission inventory (REAS).

### 2. OUTLINE OF CMAQ SIMULATION AND EMISSION INVENTORY

### *2.1 CMAQ Simulation*

The three-dimensional regional-scale CTM used in this study has been developed jointly by Kyushu University and the National Institute for Environmental Studies (NIES) (*Tanimoto et al.*, 2005, *Uno et al.*, 2006) based on the Models-3 CMAQ (ver. 4.4) modeling system released by the US EPA (*Byun and Ching*, 1999). The model is driven by meteorological fields calculated by RAMS, the Regional Atmospheric Modeling System version 4.3 (*Pielke et al.,* 1992), with NCEP/NCAR 2.5 degree × 2.5 degree reanalysis data sets at six hour intervals in 2000.

The spatial domain for CMAQ and RAMS (shown in Fig. 1) is 6240 × 5440 $km^2$ (inside domain) and 8000 × 5600 $km^2$ (outside domain) on rotated polar stereographic map projection centered at 25 ˚N, 115 ˚E with 80 × 80 $km^2$ grid resolutions, respectively. For vertical resolution, the CMAQ has the σ-z coordination system up to 23 km and 14 vertical layers.

In this study, the SAPRC-99 scheme is applied for gas-phase chemistry, and AERO3

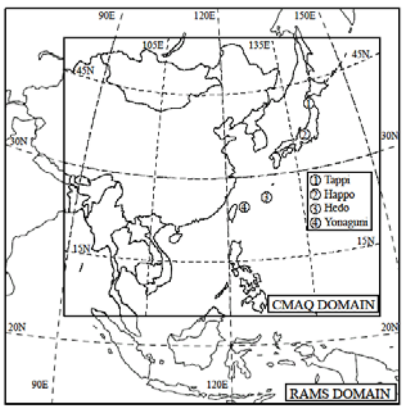


Fig.1. Model domain for the CMAQ simulation.

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module is used for aerosol calculation. The initial and lateral boundary conditions are provided from monthly averaged outputs from the CHemical AGCM for Study of atmospheric Environment and Radiative forcing, CHASER (*Sudo et al.,* 2002).

### 2.2 Emission Inventory (REAS)

Frontier Research Center for Global Change(FRCGC) and NIES have developed a Regional Emission Inventory in Asia(REAS), and publicized the dataset ver. 1.1 on a web page (http://www.jamstec.go.jp/frcgc/research/d4/emission.htm) (*Akimoto and Ohara,* 2004; *Ohara et al.* 2006). The inventory includes the data of $SO_2$, NOx, CO, NMVOC, BC, OC from fuel combustion and industrial sources, and those of NOx, $N_2O$, $NH_3$ and $CH_4$ from agricultural sources. The historical and present inventory for 1980-2000 has been developed as grid data with 0.5° by 0.5° resolution. Additionally, a future projection till 2020 has been conducted.

In constructing REAS ver. 1.1, particular concern has been paid to the coal consumption trend in China during 1996-2000, which is reportedly been decreasing according to China Energy Statistics Yearbook (CESY) and International Energy Agency (IEA) statistics. Verification of these data was made by GOME satellite observational data for tropospheric $NO_2$ column density in Northern China Plain reported by Irie et al. and Richter et al. (*Akimoto et al.* 2006). The $NO_2$ column increase from 1996 to 2002 averaged for the two reports is about 50%, whereas the NOx emission increase based on the the province-by-province data in the China Energy Statistics Yearbook (PBP-CESY) and IEA are 25 and 15 %, respectively. The country total data of CESY is even lower than the PBP-CESY and IEA. The discrepancy of the increasing trends between the satellite data and the PBP-CESY emission inventory could be within the uncertainty level with a reservation that the increase in total fuel consumption in PBP-CESY may still be underestimated particularly after the year of 1999. After these verification, we adopted the energy consumption data of PBP-CESY to develop REAS ver. 1.1.

Future projection of Asian emission was performed based on socioeconomic scenarios (energy consumption, GDP growth rate, population increment, the other activity growth rates, and implementation trend of emission control) and emissions for the year 2000. Three emission scenarios were developed for the years 2010 and 2020. The first scenario is termed the Reference scenario, or [REF]. This presents our “best guess”, as to what emissions in Asia will be in the years 2010 and 2020. The second scenario is termed the Policy Succeed Case scenario, or [PSC]. This means “optimistic case“, having lower emission in China. The final scenario is termed the Policy Failed Case scenario, or [PFC]. This means “pessimistic case“, having higher emission in China. We think it that energy growth and emission factors in China will be higher than those in REF scenario. The energy consumptions under the REF, PSC, and PFC scenarios were provided from the forecasts by a simulation model, Long-range Energy Alternatives Planning system (LEAP), conducted in the research project of China Energy Research Institute and National Lawrence Berkley Laboratory.

## 3. RESULTS AND DISCUSSION

### 3.1 Validation of Simulated Ozone

The reproducibility of $O_3$ concentration in the surface layer (below 150 m) simulated by CMAQ

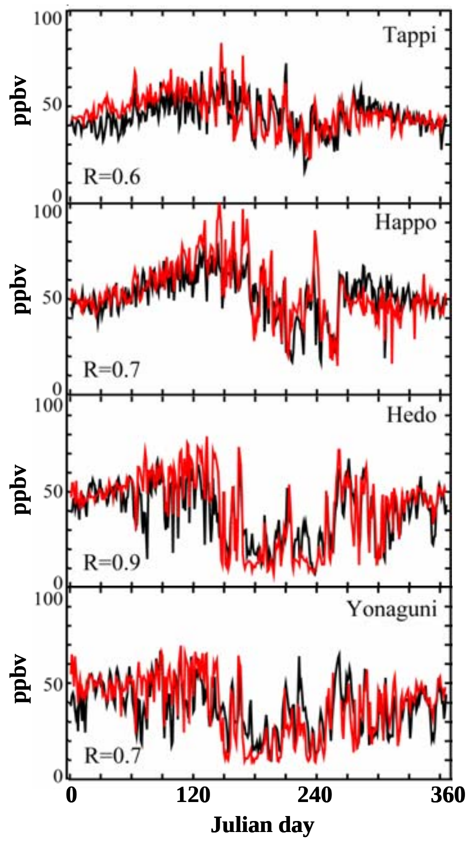


Fig.2. Observed (red) and simulated (black) daily ozone concentrations at Japanese monitoring sites during 2000.

was confirmed by comparing with observation data in 2000 at four Japanese remote monitoring sites (Tappi, Oki, Hedo, and Yonaguni) from the Acid Deposition Monitoring Network in East Asia (EANET) and from the WMO World Data Centre for Greenhouse Gasses (WDCGG) (see Fig. 1). Fig. 2 compares daily-averaged simulated $O_3$ concentrations with daily-averaged observed $O_3$ concentrations at the four monitoring sites. Our model system can catch the observed $O_3$ concentration levels and the day-to-day variations with correlation coefficients based on daily-averaged $O_3$ ranging between 0.61 and 0.85. More comprehensive and systematic validation has been conducted in *Yamaji et al.* (2006).

### *3.2 Projection of Future Emissions*

We will briefly summarize the future emissions for NOx and NMVOC in the years of 2010 and 2020. Fig. 3 shows the change of Asian regional emissions from 2000 to 2010 or 2020. Fig. 4 shows the spatial distribution for NOx and NMVOC emissions in 2000 and 2020REF.

#### 3.2.1 NOx

In the 2020REF scenario, $NO_x$ emissions in China (15.6 Tg $NO_2$ $yr^{-1}$) will increase by 39 % from 2000 (11.2 Tg $NO_2$ $yr^{-1}$). Regional $NO_x$ emissions from other East Asia and Southeast Asia will increase by 25 % from 2000 (4.4 Tg $NO_2$ $yr^{-1}$) to 2020 (5.5 Tg $NO_2$ $yr^{-1}$) and by 53 % from 2000 (5.8 Tg $NO_2$ $yr^{-1}$) to 2020 (3.8 Tg $NO_2$ $yr^{-1}$), respectively. In the 2020PSC scenario, the $NO_x$ emissions in China have a little decrease of 2 % from 2000 to 2020. This emission scenario provides more moderate reduction of $NO_x$ emissions than the IIASA Maximum Feasible Reduction (MFR) scenario, "optimistic" future situation which provided quite low $NO_x$ emission, one third of the year 2000 level in 2020 (*Cofala et al.*, 2006). In the 2020PFC scenario, $NO_x$ emissions emitted in China will increase by 51 % from 2000.

#### 3.2.2 NMVOC

In the 2020REF scenario, NMVOC emissions in China (35.2 Tg $yr^{-1}$) will increase rapidly by 139 % from 2000 (14.7 Tg $yr^{-1}$). Regional NMVOC emissions from other East Asia and Southeast Asia will increase by 70 % from 2000 (3.7 Tg $yr^{-1}$) to 2020 (6.3 Tg $yr^{-1}$) and by 53 % from 2000 (11.1 Tg $yr^{-1}$) to 2020 (19.1 Tg $yr^{-1}$), respectively. In the 2020PSC scenario, the NMVOC emissions emitted in China have a large increase of 97 % from 2000. In the 2020PFC scenario, NMVOC emissions emitted in China will increase by 163 % from 2000. The control technologies and environmental policies for anthropogenic NMVOC emissions will be behind to those for $NO_x$ emission

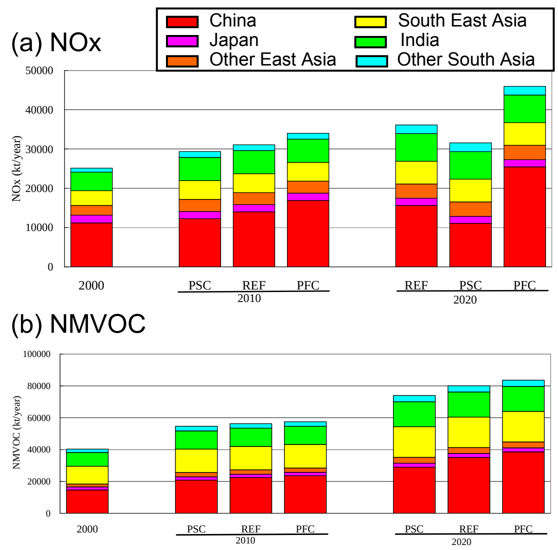


Fig.3. Asian emissions of NOx and NMVOC for 2000, 2010, and 2020. Future emissions in China only are estimated under three emission scenarios.

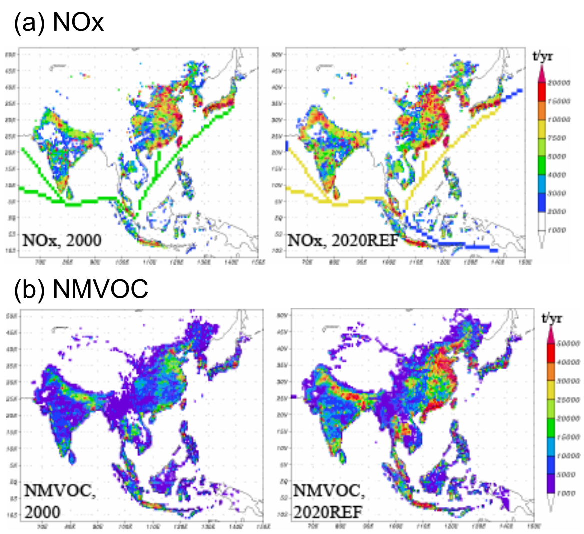


Fig.4. Spatial distributions of NOx and NMVOC emissions at 0.5 deg x 0.5 deg resolution in 2000 and 2020 reference scenario.

in many Asian countries, therefore the growth of Asian NMVOC emissions is expected to be greater in either emission scenario.

### *3.3 Future Ozone*

Future projections of surface ozone over East Asia were conducted using the CMAQ model and the REAS 1.1 emission inventory under the 2000 meteorological fields. Fig.5 shows the spatial distributions of annul-averaged $O_3$ concentrations in the boundary layer (below 2 km) over East Asia for 2000 emissions and 2020 emissions in three scenarios. Fig. 6 shows the spatial distributions of annual-averaged $O_3$ concentration changes from 2000 to 2020 under three emission scenarios: dREF (=2020REF-2000); dPSC (=2020PSC-2000); and dPFC (=2020PFC-2000).

#### 3.3.1 Spatial distributions of surface $O_3$ in 2000 and 2020REF

The difference between $O_3$ concentrations for 2000 and 2020REF is small (< 5 ppbv) over the northeast Asia (the northeast China, the Korean peninsula, and Japan) because the photochemical $O_3$ production is low, especially in winter, as presented by *Yamaji et al.* (2006). On the other hand, in the 2020REF scenario, the southern side of the model domain (latitude lower than approximately 35 °N) has enhanced $O_3$ concentrations. Especially, in the latitude belt of 20-35 °N (the coast and seashore of the southeast China), the 2020REF scenario shows an increase of nearly 5 ppbv in the $O_3$ concentration compared to the 2000 level. These increases are reflected by the increases of $NO_x$ and NMVOC emissions between 20°N -40 °N from 2000 to 2020.

Another important feature of $O_3$ increases form 2000 to 2020 is that the $O_3$ growth as well as the latitudinal zone indicating the maximum $O_3$ enhancement are strongly dependent on the season, due to the seasonal variations of meteorology in east Asia (Asian monsoon).

#### 3.3.2 Future changes of surface ozone under three emission scenarios

It is interesting to compare the spatial distribution of $O_3$ concentrations in three emission

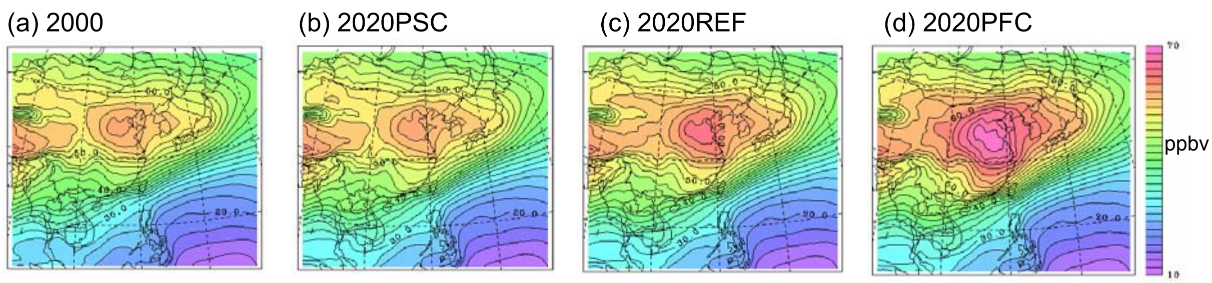


Fig.5. Spatial distributions of annual-averaged surface ozone for 2000, 2020PFC, 2020REF, and 2020PFC.

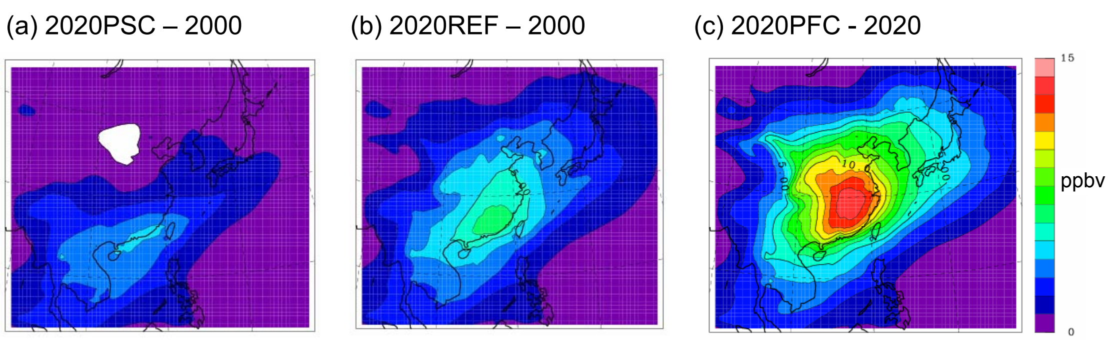


Fig.6. Spatial distributions of surface ozone changes between 2000 and 2020 under the PFC, REF, and PFC scenarios.

scenarios, REF, PSC, and PFC, for the year 2020. The spatial distribution of dPSC (=2020PSC-2000) is quite different from the others and shows a little decrease of $O_3$ concentrations over northeast parts of China. This is affected by a decrease of $NO_x$ emissions in this area. Meanwhile, due to the high $NO_x$ emission growth in some mega-cities (Beijing, Tenjing, Shanghai, and HongKong), the increases of $O_3$ concentrations around these mega-cities are predicted even in PSC scenario. While, the feature of spatial distribution in dPFC(=2020PFC-2000) is close to that in dREF (=2020REF-2000) although the $O_3$ growth rates are different between these scenarios (for example, 6-12 ppbv in dREF and 18-24 ppbv in dPFC over the north China plain). We conclude that the future $O_3$ concentrations show a high sensitivity to an increase and a decrease of $NO_x$ emissions under REAS future emission scenarios.

## 4. SUMMARY AND CONCLUSIONS

Future projection of surface ozone over East Asia were conducted using the CMAQ model and the REAS (Regional Emission Inventory in ASIA) 1.1 emission inventory. The CMAQ with the REAS can reproduce the spatial and seasonal variations of the observed surface ozone concentrations in 2000. The future emission up to 2020 were projected based on the REAS and three emission scenarios. In 2020, the Chinese $NO_x$ emissions in each scenario are expected to increase by +40 %, -3 %, and +131 % from 2000, respectively. The worst scenario shows that the East Asian $NO_x$ emissions almost double between 2000 and 2020. We find that the surface ozone concentrations in East Asia will increase significantly in the near future due to projected increases in NOx and NMVOC emissions.

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