FUTURE PREDICTION OF TROPOSPHERIC OZONE OVER SOUTH AND EAST ASIA IN 2030

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1. INTRODUCTION

China, India, and other developing countries in Asia are accomplishing rapid economic growth. On the other hand, expanding economic activities have caused significant increase of energy consumption and carbon dioxide (CO_2) emissions as well as heavy air pollution. One of key air pollutants is tropospheric ozone. Ozone has adverse effects on human health and vegetation. In addition, tropospheric ozone is getting more attentions as one of short-lived climate pollutants (SLCPs). Reduction of tropospheric ozone may achieve co-benefits which would save human health and vegetation, and simultaneously mitigate near-term climate change.

The purpose of this study is to predict tropospheric ozone over South and East Asia in 2030 under future scenarios by using three-dimensional regional air quality simulations to evaluate effects of potential energy and environmental strategies implemented in China and India on tropospheric ozone over South and East Asia.

2. SIMULATION SETUP

2.1 Model configurations

The Community Multi-scale Air Quality modeling system (CMAQ) (Byun and Schere, 2006) version 5.0.1 was applied to simulate concentrations of ambient gaseous and aerosol species including ozone. Gas-phase chemistry was represented in the Carbon Bond 05 mechanism with updated toluene chemistry (CB05-TU) (Whitten et al., 2010). Meteorological inputs were obtained by running the Weather Research and Forecasting modeling system (WRF) - Advanced Research WRF (WRF-ARW) (Skamarock et al., 2008) version 3.4.1.

The target domain covers South, East, and Southeast Asian countries as shown in Fig. 1. The horizontal resolution is 60 x 60 km. 41 vertical layers are set from the ground to 5,639 Pa above (approximately 19.5 km) in WRF-ARW, and they are collapsed into 28 layers in CMAQ. The bottom layer height is approximately 34 m in both models. Boundary concentrations of CMAQ were retrieved from the results of Model for Ozone and Related chemical Tracers, version 4 (MOZART-4).

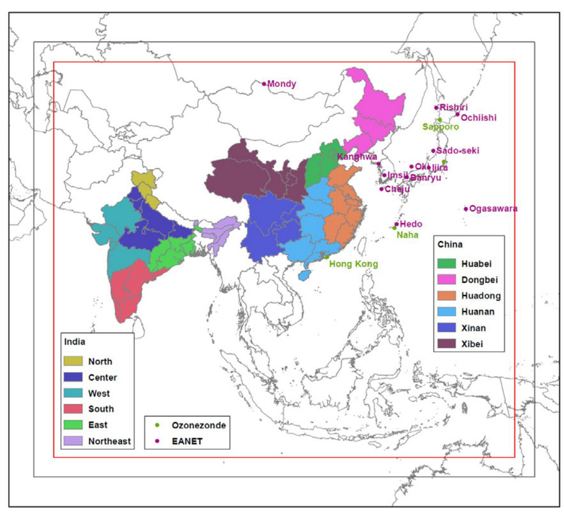

Fig. 1 Target domains of WRF-ARW (gray) and CMAQ (red). EANET and ozonezonde monitoring sites are shown. Regions in China and India are color-coded.

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All the simulations were performed for fourteen months from November 2009 to December 2010 whereas results for the first month were discarded as a spin-up period. Future changes in meteorological fields were not considered.

2.2 Energy and emission data

We estimated energy consumption and emissions of various species including CO_2 in 2010 (referred as BASE) in 22 Asian countries. We also developed three future scenarios (BAU0, PC0, and PC1). BAU0 assumed a business as usual pathway. PC0 assumed additional legislations and technological developments to suppress energy consumption and CO_2 emissions in China and India. PC1 assumed additional legislations and technological developments to improve air quality in China and India besides PC0. Differences between BAU0 and PC0, and PC0 and PC1 correspond to effects of additional energy and environmental strategies implemented in China and India, respectively.

The database of anthropogenic energy consumption and emissions in China and India has been developed by Zhao et al. (2013) and by Sharma et al. (2013), respectively. The horizontal resolution is 36 x 36 km. The data of anthropogenic energy consumption and emissions in other Asian countries than China and India were obtained from the results of the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS)-Asia model (Amann et al., 2011). The horizontal resolution is 0.5 x 0.5 degree.

Monthly values in the Global Fire Emissions Database (GFED) (Van der Werf et al., 2010) version 3.1 were applied for biomass burning emissions. Emission Database for Global Atmospheric Research (EDGAR) version 4.1 (European Commission, 2010) was applied for international shipping emissions. Hourly biogenic emissions were estimated by the Model of Emissions of Gases and Aerosols from Nature (MEGAN) (Guenther et al., 2006) version 2.04.

3. MODEL PERFORMANCE

A simulation for the case using emissions for 2010 (BASE) was performed. Horizontal distributions of the simulated seasonal mean surface ozone concentration (daily 8-hour maximum within the bottom 3 layers up to 134 m high) are shown in Fig. 2. A zone with high concentration encompasses mid-latitude regions from India to Japan in spring and autumn. It is shifted northward and the highest concentration appears around north eastern China in summer. By the contrary, the concentration significantly decreases around the same region in winter. The simulated results of ozone and related species were compared with observations to validate them.

3.1 Surface ozone

The monthly mean surface ozone concentration observed at the Acid Deposition Monitoring Network in East Asia (EANET) sites (Network Center for EANET, 2012) and the corresponding values simulated in the bottom layer are compared as shown in Fig. 3.

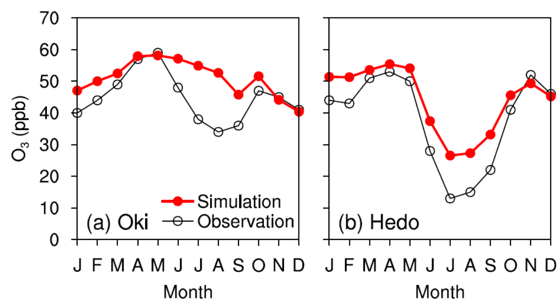

Fig. 3 Comparison of observed and simulated monthly mean surface ozone concentration at two EANET sites (Oki and Hedo in Japan).

The observed values are high in spring and low in summer. Similar seasonal variations are found in the simulated values. However, the low values observed in summer were overestimated in

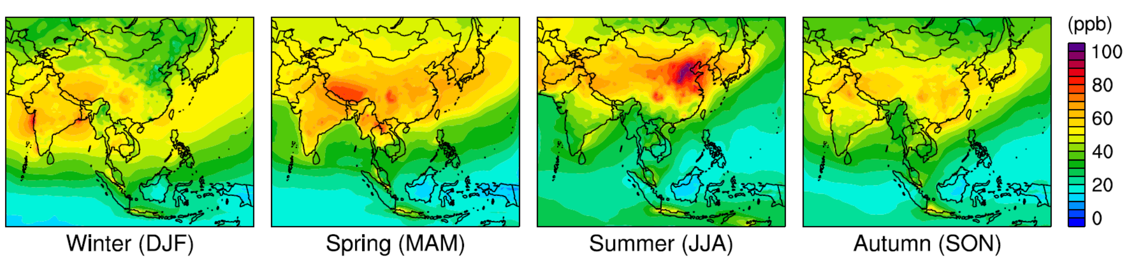

Fig. 2 Horizontal distributions of simulated seasonal mean surface ozone concentration in BASE.

the simulation at several sites whereas the values in other seasons were well reproduced. Excess ozone around northeastern China may be transported downwind to South Korea and Japan on westerly winds and cause overestimation. In addition, the boundary ozone concentration retrieved from the results simulated by MOZART-4 over the southern Pacific Ocean may be overestimated and have influenced downwind regions of southerly winds.

3.2 Vertical ozone profile

Vertical concentration profiles of the simulated ozone at Tsukuba, Japan were compared with those of the ozone observed by ozonesonde as shown in Fig. 4. High gradients of the values observed in the upper troposphere were well reproduced by the simulation. The older versions of CMAQ had a problem in simulating them adequately when results of global scale models were utilized as boundary concentrations (Lam and Fu, 2009). It appears the performance on vertical profile has been much improved in the latest version of CMAQ. The profiles in the lower and middle troposphere were also well reproduced, but the simulated values are slightly higher around the surface and lower in the middle troposphere than the observed values except for winter. Underestimated vertical diffusion may have caused excessive accumulation of ozone in lower layers in the simulation.

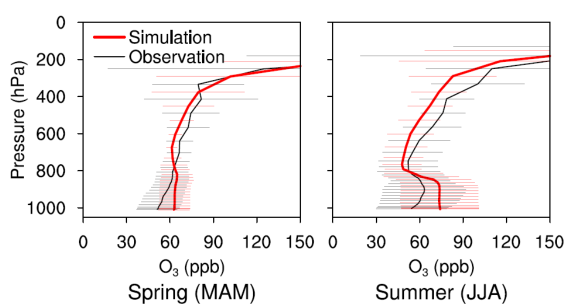

Fig. 4 Comparison of seasonal mean vertical concentration profiles of observed and simulated ozone at Tsukuba, Japan.

4. FUTURE PREDICTION

Simulations for the nine cases shown in Table 1 were performed to examine various factors on surface ozone in 2030. Future changes of surface ozone from 2010 to 2030 were evaluated in BASE and BAU0 cases. Only NOx and VOC emissions were changed from BASE to BAU0 in BAU0nox and BAU0voc cases, respectively, to evaluate their effects separately. Boundary ozone concentration was homogeneously increased by 5 ppb in BAU0o3 to evaluate potential effects of increasing background ozone on tropospheric ozone within the target domain. Similarly, homogeneous methane concentration was increased by 400 ppb from the value used in the default CMAQ (1850 ppb) in BAU0ch4 to evaluate potential effects of increasing background methane. Temperature was homogeneously decreased by 5 degC in BAU0ta to see sensitivities of temperature on surface ozone. Effects of the additional energy and environmental strategies on surface ozone in 2030 were evaluated in PC0 and PC1.

Table 1 Overview of simulation cases performed in this study.

Case	Emission	Other change
BASE	BASE	
BAU0nox	BAU0 (NOx only) + BASE	
BAU0voc	BAU0 (VOC only) + BASE	
BAU0	BAU0	
BAU0o3	BAU0	+ 5ppb boundary ozone
BAU0ch4	BAU0	+ 400ppb background methane
BAU0ta	BAU0	- 5degC temperature
PC0	PC0	
PC1	PC1	

4.1 Future surface ozone in the BAU scenario

Horizontal distributions of differences in the simulated seasonal mean surface ozone concentrations between BAU0nox and BASE, BAU0voc and BASE, and BAU0 and BASE are shown in Fig. 5. Significant increase of surface ozone around India in BAU0 is evident in all seasons. Surface ozone around north eastern China in BAU0 is similarly higher in summer whereas it is slightly lower in winter than BASE. Increase of surface ozone around India and surrounding regions including south western China and Indochina in all seasons is exclusively affected by increasing NOx. The effects of VOC are negligible or slightly negative around those regions. Increase of surface ozone over most of China in summer is also much affected by increasing NOx. On the other hand, negative

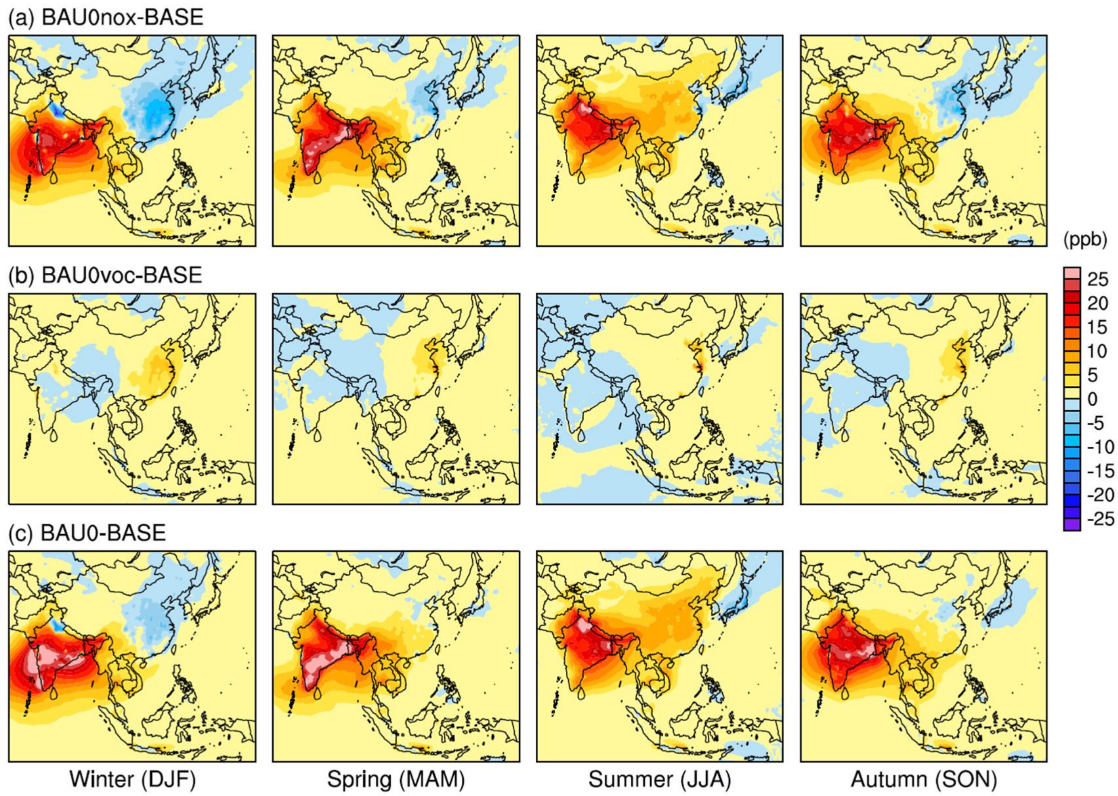

Fig. 5 Horizontal distributions of differences in simulated seasonal mean surface ozone concentrations between (a) BAU0nox and BASE, (b) BAU0voc and BASE, and (c) BAU0 and BASE.

effects of increasing NOx appear around north eastern China in spring and autumn, and they expand to whole eastern China in winter. Increasing VOC has positive effects around the corresponding regions.

4.2 Effects of external factors on future surface ozone

The effect of boundary ozone is reduced around regions where a lot of chemical species are emitted and react with ozone in BAU0o3. Decrease of the effect is more evident in summer due to more active photochemical reactions. The effect is also lower around tropical regions with abundant water vapor. Nevertheless, increasing boundary ozone may cause a few ppb increase of surface ozone throughout the domain. By contrast, the effect of background methane increases around regions where a lot of chemical species are emitted in BAU0ch4. However, magnitude of the effect of background methane is only a few ppb at a maximum against a large increase of background methane (+400 ppb). It is compensated with effect of boundary ozone, and combined effects of boundary ozone and background methane do not exceed 5 ppb.

Negative effect of decreased temperature is found around regions where surface ozone is abundant such as India for whole year and north eastern China in summer in BAU0ta. It means that higher temperature is one of factors which cause higher ozone concentration. The weather condition around India is warm throughout the year. Therefore, increase of precursor emissions has larger importance in terms of ozone formation in India.

4.3 Effects of energy and environmental strategies on future surface ozone

Horizontal distributions of differences in the simulated seasonal mean surface ozone concentrations between PC0 and BAU0 and PC1 and BAU0 are shown in Fig. 6. Surface ozone is effectively reduced by the additional energy and environmental strategies around the regions in which it significantly increases from BASE to BAU0. Though, the regions with increasing ozone are found around eastern China. They do not mean that energy and environmental strategies

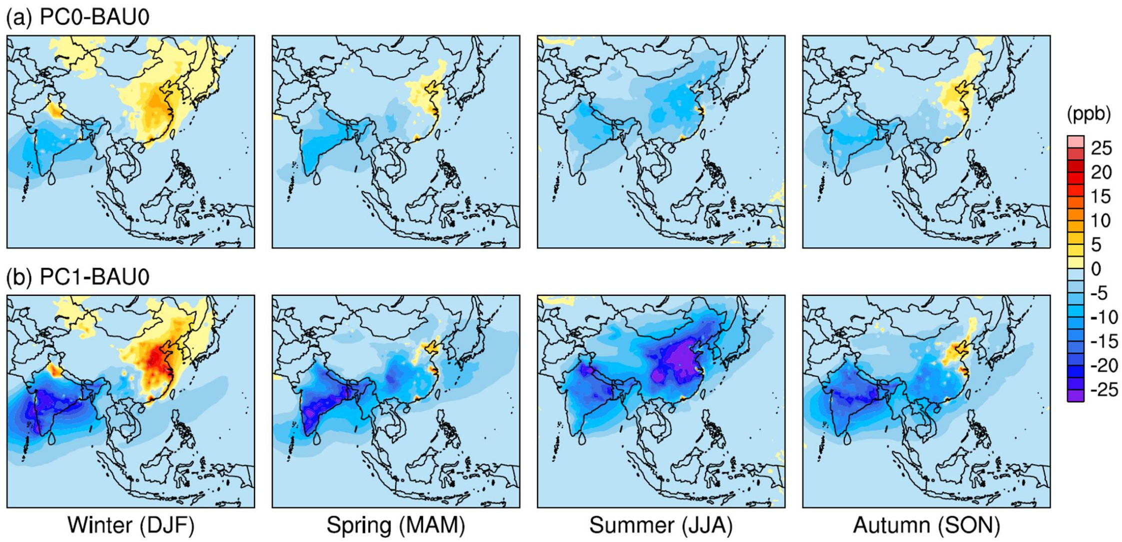

Fig. 6 Horizontal distributions of differences in simulated seasonal mean surface ozone concentrations between (a) PC0 and BAU0, and (b) PC1 and BAU0.

are not preferable to mitigate air pollution. Ozone isopleths against NOx and VOC have non-linear shapes (Sillman, 1999). If NOx is reduced in VOC-sensitive regime, ozone should increase until it goes into NOx-sensitive regime. It is essential to reduce NOx to pass over the ridge which divides VOC- and NOx-sensitive regimes and go into NOx-sensitive regime where ozone is effectively reduced. The regions with increasing ozone are shrunk in spring and autumn. They imply that regime of ozone chemistry changes from VOC-sensitive to NOx-sensitive due to effective reduction of NOx.

4.4 Regional summary

Figure 7 shows the differences in the simulated annual mean surface ozone concentrations among cases which are averaged over regions in China and India as well as other major countries. Note that the ranges of vertical axis are different in East Asia (left) and South and Southeast Asia (right). Surface ozone increases from BASE to BAU0, and is effectively reduced in PC0 and PC1 in western China (Xinan and Xibei) as well as in India. On the other hand, the positive and negative effects of increasing NOx in BAU0 in summer and winter are cancelled out in eastern

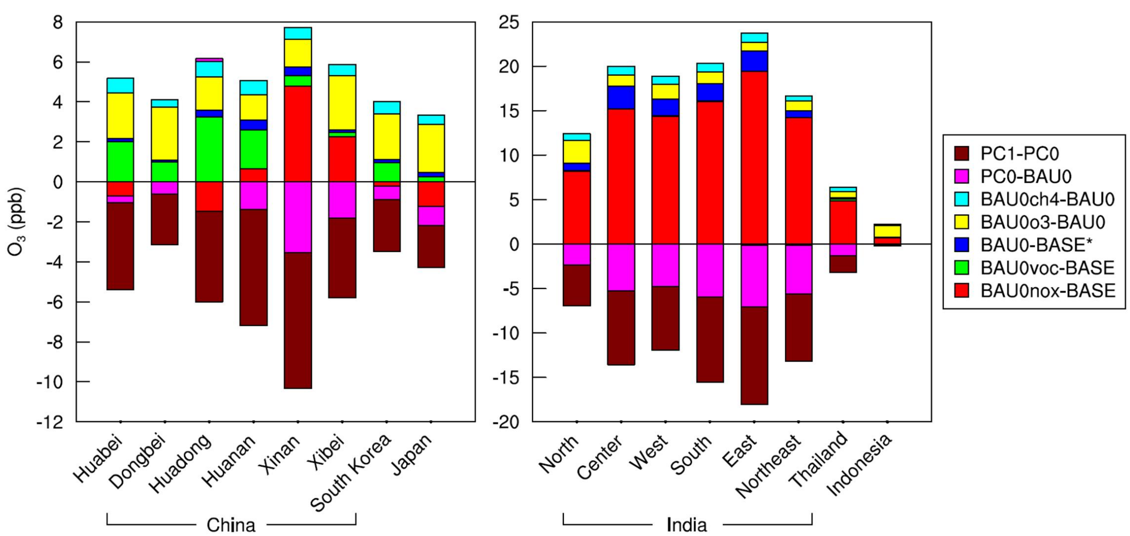

Fig. 7 Differences in simulated annual mean surface ozone concentrations among cases which are averaged over regions in China and India as well as Japan, South Korea, Thailand, and Indonesia.

China (Huabei, Dongbei, Huadong, and Huanan), and the effects of increasing VOC are relatively larger. The small effects of PC0 in eastern China are also due to its opposite effects in summer and winter. In addition, relative importance of background ozone and methane is also larger in East Asia. Overall and well-designed strategies are required to effectively reduce annual mean surface ozone in East Asia.

5. CONCLUSIONS

This study constructed a regional air quality simulation framework to simulate tropospheric ozone over South and East Asia. It demonstrated acceptable performance on tropospheric ozone while overestimation of low concentration in summer is one of remaining issues which other simulation studies are also facing.

The simulations predicted significant increase of surface ozone around India in BAU0. Increasing NOx due to expanding economic activities was a major cause, and warmer weather contributed to it. Surface ozone was predicted to increase also around north eastern China in summer due to increasing NOx in BAU0. The additional energy and environmental strategies assumed in PC0 and PC1 are expected to effectively reduce surface ozone in the seasons and regions in which surface ozone is significantly increased in BAU0. The situation is a bit complex for annual mean surface ozone in East Asia. Increasing VOC as well as increasing background ozone and methane are also important for it.

Various energy and environmental strategies are assumed in PC0 and PC1. It is desired to implement them to suppress tropospheric ozone over South and East Asia. Energy strategies assumed in PC0 could simultaneously suppress energy consumption and CO_2 emissions.

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