Development of a One-way Nested Global-regional Air Quality Forecasting Model

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Abstract

We evaluated the ozone distribution over the Kanto region in Japan, calculated by a one-way nested global-regional air quality forecasting (AQF) system. This AQF system consists of global and regional chemistry-transport models (CTMs). The global CTM is based on CHASER (Chemical Atmospheric General Circulation Model for the Study of Atmospheric Environment and Radiative Forcing) model, whereas the regional CTM is based on the WRF (Weather Research and Forecasting)/Chem model. The lateral boundary of the regional CTM domain is updated every 3 hours from the global CTM output. An experimental phase for this model system began in July 2006 and has provided 15-hour forecasts of the distribution of ozone concentrations over the Kanto region four times daily. The time evolution and horizontal distribution of chemical species calculated by this AQF system were compared to ground-based observations. Values of statistical measures are within the range suggested by the U.S. Environmental Protection Agency (EPA). By changing the initial value of the meteorological field from 6-hour forecast values to an analysis meteorological field, the average value of the correlation coefficient increased from 0.763 to 0.773.

1. Introduction

Ozone has been recognized as a harmful pollutant for decades (e.g., Haagen-Smit et al. 1951). However, until recently, it has been difficult to apply numerical air quality models for routine forecasting of air quality because of the high computational costs of calculating the transport and transformation of chemical species. Some studies have used regional chemistry-transport models (CTMs) for air quality forecasting (e.g., Uno et al. 2003; de Freitas et al. 2005; Eder et al. 2006). Regional CTMs have an advantage in horizontal resolution over global models. On the other hand, global CTMs have the major advantage of being able to estimate intercontinental transport (cf., Lawrence et al. 2003; Takigawa et al. 2005). Takigawa et al. (2005) estimated the contribution of intercontinental and regional long-range transport of CO to East Asian Pacific rim region. The concentration of surface ozone over Japan is strongly affected by regional transport from East Asian emissions especially in summer (Pochanart et al. 1999). Thus, it is important to consider intercontinental as well as regional transports of pollutants in forecasting air quality over Japan.

In addition to synoptic-scale meteorology, fine-scale meteorology and advection play key roles in the distri-

bution of ozone and its precursors over the Kanto plain, which covers the Tokyo metropolitan area (Uno et al. 1996). A global-regional nested model is able to treat long-range transport, in situ chemistry, and local-scale transport within the polluted area simultaneously. Wang et al. (2004) showed that the modeled CO mixing ratio was improved by applying a nested domain to the global CTM with simple chemistry for CO, mainly by the improvement of meteorological features.

We have developed a one-way nested global-regional AQF system with full chemistry based on the CHASER (Sudo et al. 2002) and WRF/Chem (Grell et al. 2005) models. Here, we describe and evaluate our model system.

2. Numerical model system

The global CTM part is based on the CHASER model, which is based on CCSR/NIES/FRCGC atmospheric general circulation model (AGCM) version 5.7b. The basic physical and dynamical features of the model have been described by Hasumi et al. (2004), and modifications of the chemical and dynamical features have been described by Takigawa et al. (2005). Spectral coefficients are triangularly truncated at wavenumber 42 (T42), equivalent to a horizontal grid spacing of about 2.8°. The model has 32 vertical layers that are spaced at approximately 1-km intervals in the free troposphere and lower stratosphere.

The regional CTM part is based on WRF/Chem (Grell et al. 2005). Anthropogenic emission data over Japan, except those from automobiles, are from the JCAP (Japan Clean Air Program) with 1 km × 1 km resolution (Kannari et al. 2007), and anthropogenic emissions from automobiles over Japan are from EAgriid 2000 (East Asian Air Pollutant Emissions Grid Inventory) with 1 km × 1 km resolution (K. Murano, personal communication). Surface emissions over China and North and South Korea are taken from REAS (Regional Emission Inventory in Asia) with 0.5° × 0.5° resolution (Ohara et al. 2007), and surface emissions over Russia are taken from EDGAR (Emission Database for Global Atmospheric Research) with 1° × 1° resolution (Olivier et al. 1996). Diurnal and seasonal variations in surface emissions are taken into account in the JCAP and EAgriid2000 data, and diurnal variations are also parameterized in emissions from REAS and EDGAR following averaged variations of JCAP. Weekly variation between workdays and holidays is also taken into account in the EAgriid2000 automobile emission data. Note here that emissions based on the statistics in 2000 are applied in the present study. Biogenic emissions are based on Guenther et al. (1993). Figure 1 shows the model domain for the regional CTM part. The outer domain covers Japan with 15-km horizontal resolution (152 × 152 grids for chemical species), and the inner domain covers the Kanto region with 5-km resolution (111 × 111 grids for chemical species). The inner and outer domains in the regional CTM have 31 vertical

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Fig. 1. Model domains for the regional CTM part. The outer domain covers Japan with a 15-km horizontal resolution, and the inner domain covers the Kanto region with a 5-km resolution.

layers up to 100 hPa. The two-way nesting calculation is applied in the regional CTM part.

The lateral boundary of chemical species in the regional CTM is taken from the global CTM. The output of the global CTM is linearly interpolated from the Gaussian latitude and longitude grid to a Lambert conformal conic projection for use in the regional CTM. The lateral boundary is updated every 3 hours and linearly interpolated for each time step. We did not include feedback from the regional CTM to the global CTM; that is, the one-way nesting calculation was done between the global and regional CTMs.

The system is driven by meteorological data from the National Centers for Environmental Prediction (NCEP) for the global CTM part and from the mesoscale model (MSM) of the Japan Meteorological Agency (JMA) for the regional CTM part. A 15-hour forecast has been produced four times daily at 00, 06, 12, and 18Z with a lead time of 8–10 hours since July 2006, following a spin-up of 1 month for the global distribution of chemical species. The initial condition of the meteorological field for the regional CTM was taken from the MSM for each forecast, and the initial condition of chemical species was taken from the model output driven by the analysis meteorology.

3. Results

To evaluate the model-calculated ozone, the surface ozone mixing ratio was compared to that observed at air quality monitoring stations. There are 251 stations observing surface ozone within the inner domain of the regional CTM as of August 2006. For the comparison of temporal variation, hourly averaged values of observed and modeled surface O_3 mixing ratios in August 2006 are shown in Fig. 2. Observed ozone exceeded 100 ppbv

from 3 to 6 August at Hanyuu in Saitama Prefecture ($36^{\circ}10'28''N$, $139^{\circ}33'21''E$, upper panel of Fig. 2), which is downwind of the Tokyo metropolitan area. The maximum value in the observation was 162 ppbv at 16Z on 3 August. The model successfully reproduced the ozone maximum on 3 August. The maximum simulated value was 137 ppbv in the model. The model also successfully captured the decrease from 3 to 7 August, but failed to show the rapid decrease on 8 August. Three typhoons (Maria, Somai, and Bopha) occurred during this period, and the difficulty of predicting the meteorological field may have led to the overestimation of ozone on 8 August. Both the model and observations indicate low levels of ozone from 14 to 17 August as typhoon 200610 (Wukong) approached Japan. The observed and modeled ozone exceeded 100 ppbv on 11 and 13 August, and the model overestimated the ozone mixing ratio on 19 August. The modeled ozone mixing ratio was 135 ppbv, whereas the observed ozone mixing ratio was 86 ppbv. Daily variation in the ozone mixing ratio at nighttime was well reproduced by the model. The daily minimum of observed and modeled ozone exceeded 10 ppbv on 12, 15, 27, and 28 August; except for these days, the ozone level was almost zero during nighttime. The comparison between the modeled and observed daily variation in surface ozone at Kodaira in Tokyo ($35^{\circ}43'42''N$, $139^{\circ}28'38''E$) is shown in the lower panel of Fig. 2. Maxima of observed and modeled surface ozone at Hanyuu appeared on 3 August, and the observed and modeled ozone mixing ratios at Kodaira were 140 ppbv or higher on 5 and 6 August. The model tended to overestimate the daytime ozone maximum especially for cloudy days, and the discrepancy of daily maximum is larger in urban area compared to that in rural area. To evaluate the model performance, a set of statistical measures provided by the U.S. Environmental Protection Agency (US EPA 1991) was evaluated for stations in the inner domain of the model. The mean normalized bias error (MNBE), the mean normalized gross error (MNGE), and the unpaired peak prediction accuracy (UPA) were 7.1%, 9.5%, and 9.4%, respectively. These values are within the criteria range suggested by the U.S. EPA ($MNBE < \pm 10\text{--}15\%$, $MNGE < \pm 30\text{--}35\%$, and $UPA < \pm 15\text{--}20\%$).

Figure 3 shows the horizontal distribution of observed and modeled surface ozone mixing ratios at 05Z (14 Japan Standard Time [JST]) on 4 August 2006. The observed ozone mixing ratio exceeded 120 ppbv at almost all stations in the western part of Tokyo metropolitan area and the eastern part of Saitama prefecture. The model captured the horizontal distribution of the observed ozone mixing ratio, but the location of the most polluted area was slightly biased westward.

Because 15-hour forecasts have been produced four times daily, each time period was covered by model outputs driven by forecasted and analyzed meteorological fields for the initial condition and lateral boundary. To evaluate the impact of the meteorological field on the distribution of surface ozone, correlation coefficients, MNBE, MNGE, and UPA between observed and modeled surface ozone at 251 stations in the Kanto area in August 2006 were compared among model outputs driven by forecast and analysis meteorological fields. Model outputs driven by the following meteorology were compared: (a) forecast meteorology for the initial condition and lateral boundary, (b) analysis meteorology for the initial condition and forecast meteorology for lateral boundary, and (c) analysis meteorology for the initial condition and lateral boundary. Table 1 shows statistical measures of model performance for surface ozone. Differences between (b) and (c) were quite small for all statistical measures. For both (b) and (c), the

Fig. 2. Hourly observed (black) and modeled (red) surface O_3 mixing ratio in August 2006 at Hanyuu in Saitama Prefecture (upper panel) and Kodaira in Tokyo (lower panel).

Fig. 3. Observed (colored dots) and modeled (color tones) surface O_3 mixing ratio at 05Z(14JST) on 4 August, 2006.

Table 1. Statistical measures of model performance for 1-h ozone concentration for the model was driven by 06–11 hour forecasts (a), 00–05 hour forecasts (b), and analysis meteorology (c).

	correlation	MNBE(%)	MNGE(%)	UPA(%)
(a)	0.76	6.5	9.4	14.0
(b)	0.77	7.1	9.5	9.5
(c)	0.77	7.1	9.5	9.4

initial condition for the meteorological field was analysis meteorology, and the difference in the relatively short-range forecast (less than 6 hours) of ozone distribution caused by the difference in the lateral boundary was negligibly small. In contrast, UPA increased in (a) compared to (b) and (c), at 14.0% in (a), and 9.5% and 9.4% in (b) and (c), respectively. These results suggest that the initial condition of the meteorological field can affect the short-range (less than 12 hours) forecast of ozone distribution. Although the forecasted ozone derived from (a) had smaller correlations than (b) and (c), approximately 83% of stations in the Kanto region had correlations of 0.70 or higher.

4. Summary and discussion

A one-way, nested, global-regional AQF system was developed to simultaneously treat long-range transport and local transport and in situ chemistry over the Kanto plain. The model system produced 15-hour forecasts of the distribution of chemical species since July 2006. Comparison of the modeled surface ozone with observations from air quality monitoring stations in August 2006 shows that the model generally reproduced diurnal and daily variations in ozone over the Kanto plain. The model could not reproduce ozone levels during typhoon events, suggesting that improvements to the meteorological part of the regional model are needed for more precise air quality forecasting. To estimate the effect of the meteorological field on air quality forecasting, the distribution of correlation coefficients was compared among model outputs that had been driven by analysis and forecast meteorological fields. The result suggests that the lateral boundary of the meteorological field may have little effect on the distribution of surface ozone, but the initial condition of the meteorological field can affect the distribution of surface ozone. Values of statistical measures such as MNBE, MNBE, and UPA are within the range suggested by the U.S. EPA. This result encourages us to apply our model as a public warning for oxidants.

One approach for improving air quality forecasts is the use of an ensemble forecast system (Monache and Stull 2003; Wilczak et al. 2006). The initial condition of chemical species is also a key factor for air quality forecasts. Data assimilation such as by the ensemble Kalman filter (EnKF; Evensen 1994) or four-dimensional variational data assimilation (4D-Var) would be useful for the initialization of the chemistry field.

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