Effect of rising Asian emissions on surface ozone in the United States

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Abstract. The effect of increasing fossil fuel combustion in eastern Asia on surface O\textsubscript{3} air pollution in the United States is examined with a global three-dimensional tropospheric chemistry model. Tripling of Asian anthropogenic emissions from 1985 to 2010 is expected to increase monthly mean O\textsubscript{3} concentrations by 2–6 ppbv in the western United States and by 1–3 ppbv in the eastern United States, the maximum effect being in April–June. This increase would more than offset the benefits of 25% domestic reductions in anthropogenic emissions of NO\textsubscript{x} and hydrocarbons in the western United States. Asian influence may be less under the stagnant conditions leading to violations of the U.S. air quality standard. Nevertheless, our results suggest that a global perspective is necessary when designing a strategy to meet regional O\textsubscript{3} air quality objectives.

1. Introduction

The U.S. national air quality standard for O\textsubscript{3} concentrations in surface air was revised in 1997 from 120 ppbv (1-hour average, not to be exceeded more than once per year) to 80 ppbv (8-hour average, not to be exceeded more than three times per year). Nonattainment areas under the old standard were mainly urban and suburban, or downwind of large metropolitan centers [EPA, 1996a]. The new standard expands the geographical scale of the regulatory problem. Saylor et al. [1998] find that many rural areas of the United States that were in compliance with the old standard will likely fail the new standard.

As the O\textsubscript{3} air quality standard decreases, better understanding of the O\textsubscript{3} background becomes increasingly important in the design of air pollution control strategies. Background O\textsubscript{3} concentrations in surface air over the United States, as derived from measurements at clean sites or from the intercept of correlations between O\textsubscript{3} and NO\textsubscript{y} (total reactive nitrogen oxides), are in the range 25–55 ppbv [Logan, 1989; Altshuller and Lefohn, 1996; Hirsch et al., 1996]. This background can be largely attributed to transport from outside the United States, and it probably includes a major anthropogenic component. Model simulations show that with zero NO\textsubscript{x} emissions in North America, and emissions elsewhere at present-day levels, long-range transport from outside the continent would maintain 20–40 ppbv O\textsubscript{3} in surface air over the United States in summer [Liang et al., 1998]. The lifetime of O\textsubscript{3} in the free troposphere is sufficiently long that pollution from Europe, Asia, and North America can circumnavigate the globe and elevate O\textsubscript{3} throughout northern midlatitudes. Measurements in the free troposphere at mountain sites over Europe show O\textsubscript{3} concentrations rising from 10 ppbv in 1890 to 20 ppbv in 1930 to 50 ppbv today [Marenco et al., 1994].

We present here a modeling investigation of the effect of rising Asian emissions on O\textsubscript{3} concentrations in surface air over the United States. Energy consumption in China, India, and most of the rest of Asia increased by 5% yr\textsuperscript{-1} over the period 1970–1995, and this rate of growth is expected to continue at least until 2015 [United States Department of Energy, 1997]. Fossil fuel combustion is the main source of emissions in Asia and proceeds with minimal emission controls except in Japan. We may therefore expect NO\textsubscript{x} and hydrocarbon emissions to grow in parallel to fossil fuel combustion. In contrast, little change is expected in U.S. emissions of NO\textsubscript{x} over the next decade [EPA, 1996b]. An emission inventory for eastern Asia (east of Afghanistan) gives a fossil fuel combustion source of NO\textsubscript{x} of 4.2 Tg N yr\textsuperscript{-1} in 1985 [Kato and Akimoto, 1992], as compared to 6.3 Tg N yr\textsuperscript{-1} in the United States [EPA, 1996b]. Kato and Akimoto [1992] report a 5.5% yr\textsuperscript{-1} growth of NO\textsubscript{x} emissions in eastern Asia outside Japan from 1975 to 1987. Assuming a 5% yr\textsuperscript{-1} growth outside Japan from 1985 to 2010, we expect the east Asian source of NO\textsubscript{x} in 2010 to amount to three times the 1985 Asian source and twice the U.S. source. Even a small contribution of this increasing Asian source to surface O\textsubscript{3} concentrations in the United States would make it more difficult for the United States to meet its air quality standard.

2. Model

Our analysis uses the Harvard-GISS global three-dimensional model of tropospheric chemistry. This model uses a 1-year archive of meteorological fields from a general circulation model (GCM) developed at the Goddard Institute for Space Studies (GISS) [Hansen et al., 1983]. The horizontal resolution is $4^\circ \times 5^\circ$. There are nine sigma levels in the vertical; the three lowest levels extend approximately to 0.5, 1.2, and 2.7 km above the surface. Meteorological information is updated every 4 hours. The model is too coarse to resolve urban plumes, but it shows some ability at simulating regional O\textsubscript{3} pollution episodes in the eastern United States [Jacob et al., 1993].

We use here the latest version of the model described by Horowitz and Jacob [1999] which includes 80 species (24 chemical tracers) to describe tropospheric O\textsubscript{3}-NO\textsubscript{x}-hydrocarbon chemistry. The chemical mechanism is integrated with a fast Gear solver [Jacobson and Turco, 1994]. The model includes comprehensive inventories of anthropogenic and natural emissions. Emissions from fossil fuel combustion are from the 1985 Global Emission Inventory Activity (GEIA) inventory for NO\textsubscript{x} [Benkovitz et al., 1996].
and the Piccot et al. [1992] inventory for hydrocarbons. The GEIA inventory for eastern Asia is that of Kato and Akimoto [1992].

Global evaluation of the model with observations for O$_3$ and its precursors was presented by Wang et al. [1998]. The model reproduces well the general climatology of tropospheric ozone determined from ozone-sonde observations. A more specific evaluation with surface observations over the United States was presented by Horowitz et al. [1998] for summer and by Liang et al. [1998] for other seasons. The model reproduces observed monthly mean concentrations of O$_3$ at non-urban U.S. sites usually to within 10 ppbv. The largest discrepancy is in the south-central United States in summer where the model overestimates O$_3$ by more than 20 ppbv. This overestimate is due to a northeastward displacement of the Bermuda High in the GCM relative to its climatological position.

In this work, we conduct a sensitivity simulation for the year 2010 where the fossil fuel combustion source from Asia east of 60°E (from Afghanistan eastward) is tripled from 1985 levels, while emissions from North America and Europe are held at 1985 levels. We also conduct sensitivity simulations where anthropogenic emissions of NO$_x$ and nonmethane hydrocarbons (NMHCs) in the United States are reduced by 25% from 1985 levels, with Asian emissions either at 1985 levels or at 2010 levels. We conduct a further sensitivity simulation with zero anthropogenic emissions in eastern Asia and 1985 levels elsewhere (zero case). All simulations are conducted for a period of 15 months from June 1 (year 1) to August 31 (year 2) using the same meteorological archive. The first 9 months of simulation are for initialization. We report results for March through August of year 2.

3. Results and discussion

Figure 1 shows the increases in monthly mean O$_3$ concentrations over the United States in March-August caused by tripling of anthropogenic emissions in eastern Asia from 1985 to 2010. Results are for the lowest model layer (0–500 m above the surface). The maximum increase is 5–6 ppbv over California in May. The increases are larger in the western United States (2–6 ppbv) than in the east (1–3 ppbv), reflecting the prevailing flow in the lower troposphere during spring and summer. The western United States are usually under the influence of westerly flow from the Pacific, while the eastern United States are usually under the influence of southerly flow from the Gulf of Mexico. Summer maxima of Asian influence over the western deserts (Figure 1) are due to strong dry convection entraining Asian pollution from aloft. Comparison of the 2010 case to the simulation with no anthropogenic Asian emissions (zero case) shows similar geographical patterns of Asian enhancement but doubled in magnitude. Tripling of Asian emissions from 1985 to 2010 thus doubles the magnitude of the Asian enhancement over the United States.

Subsidence of Asian O$_3$ transported in the free troposphere is the principal mechanism for Asian influence on surface O$_3$ over the United States in the model. Subsidence of Asian NO$_x$ and PAN followed by O$_3$ production in the U.S. boundary layer is far less important. We find that increasing Asian emissions cause a slight decrease of NO$_x$ concentrations in surface air over the United States because the higher O$_3$ concentrations lead to a shorter chemical lifetime of NO$_x$. Ozone concentrations in the free troposphere (700–300 hPa) over the United States and the extra tropical North Pacific increase by 5–10 ppbv as Asian emissions triple from 1985 to 2010 (Figure 2).

Figure 2. Increase of O$_3$ concentrations (ppbv) at 34°N caused by tripling of anthropogenic emissions in eastern Asia from 1985 to 2010. Values are model monthly means for May and July and are shown as a function of longitude (degrees) and pressure. The dashed lines are the boundaries of the United States.
Asian pollution influence on surface air in the United States is maximum in April-June (Figure 1). In summer, deep monsoonal convection over eastern Asia and relatively weak westerlies shift the Asian pollution plume to higher altitudes and limit its long-range transport (Figure 2). Westerly transport of Asian air across the North Pacific is known to be strongest in the spring (D. Jaffe, personal communication, 1999). Measurements by Jaffe et al. (1999) on the northwest coast of the United States in March-April reveal events of Asian pollution characterized by high CO and hydrocarbons; O\textsubscript{3} was not enhanced in these events, but more recent aircraft observations at the same location in spring show high O\textsubscript{3} layers associated with Asian pollution [D. Jaffe, personal communication, 1999].

Our model features little day-to-day variability (only a few ppbv) in the Asian pollution enhancement of O\textsubscript{3} concentrations over the United States. This result reflects an erroneous constancy of the GCM air flow in the free troposphere. The insufficient transport from the free troposphere. The insuficient GCM air flow in the free troposphere.

Figure 3. Changes of O\textsubscript{3} concentrations (ppbv) in surface air over the United States relative to 1985 values when 25% domestic reductions in anthropogenic NO\textsubscript{x} and nonmethane hydrocarbon (NMHC) emissions are implemented, with Asian emissions at 1985 levels (left panels) and at 2010 levels (right panels). Values are model monthly means for May (top) and July (bottom).

Our model analysis thus suggests that increasing fossil fuel combustion in eastern Asia over the next decades will cause significant degradation of mean air quality in the western United States, with less effect in the east. From the perspective of meeting the air quality standard, it is critical to determine how the Asian influence correlates on a day-to-day basis with the stagnant weather conditions conducive to O\textsubscript{3} pollution episodes. One might expect a negative correlation [Jacob et al., 1993] since pollution episodes are usually associated with strong subsidence inversions suppressing transport from the free troposphere. The insufficient
weather variability in the GISS GCM does not allow us to examine this issue here. We plan to examine it in the future with a simulation driven by assimilated meteorological observations.

We have assumed that emissions of O$_3$ precursors in eastern Asia from 1985 to 2010 would grow in parallel to fossil fuel combustion. This assumption is simplistic, as the mix of anthropogenic sources will evolve. Degradation of public health and agriculture [Chameides et al., 1999] may eventually spur air pollution control measures in Asia. In our simulation for 2010 we find monthly mean surface O$_3$ concentrations over eastern Asia in the range 50–80 ppbv (spring-summer), comparable to values in the eastern United States at present. Recent O$_3$ measurements in China reported by Chameides et al. [1999] indicate episodes exceeding 100 ppbv, and model calculations reported in that same study suggest that episodes of up to 180 ppbv might be expected if emissions double.

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References


Merrill, J. T., Atmospheric long-range transport to the Pacific Ocean, Chemical Oceanography, 10, 15–50, 1989.


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