6.1 Linking Global and Regional Models to Simulate U.S. Air Quality in the Year 2050

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Abstract The potential impact of global climate change on future air quality in the United States is investigated with global and regional-scale models. Regional climate model scenarios are developed by dynamically downscaling the outputs from a global chemistry and climate model and are then used by the Community Multiscale Air Quality (CMAQ) model to simulate climatological air quality. The CMAQ model is first applied to a five-year period representing current climate and evaluated by comparison against measurements of chemically speciated fine particulate matter ($PM_{2.5}$) concentrations in the U.S. Next, the model is applied to a simulated climate for the year 2050 based on the A1B scenario developed by the Intergovernmental Panel on Climate Change (IPCC). Two five-year future simulations are conducted, one with anthropogenic emissions held at 2001 levels, and one with anthropogenic emissions reduced to emulate the A1B scenario for the developed world. In both future simulations, biogenic and other climate-sensitive emissions are varied with the simulated climate. Results for the future simulation with current emissions indicate modest decreases of 1–2 $\mu g\ m^{-3}$ $PM_{2.5}$ in most of the eastern U.S., but large decreases exceeding 10 $\mu g\ m^{-3}$ $PM_{2.5}$ are predicted for the future reduced emissions case.

Keywords Climate change, CMAQ, particulate matter

1. Introduction

Currently, regional-scale air quality models are being used to test proposed emission controls for management of air quality without regard to interannual meteorological variability or the possibility of climate change. In cases where emission controls are implemented over several decades, (e.g., U.S. Clean Air Interstate Rule). taking climate change into account could potentially lead to a different conclusion as to an optimal control strategy. Recently, a number of studies have been conducted exploring the impact of climate change on future air quality (Hogrefe et al., 2004; Stevenson et al., 2006; Liao et al., 2006; Racherla and Adams, 2006; Cooter et al., 2007; Wu et al., 2007). Nolte et al. (2008) described a study in which downscaled regional climate scenarios are created from outputs of a global climate and chemistry model and are used by the CMAQ model to simulate air quality over the U.S. under both current and future (ca. 2050) climatologies. In Nolte et al. (2008),

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modeled current ozone concentrations are evaluated against current observations and compared with predicted future concentrations. As a follow up, this study adopts the same approach in comparing modeled current particulate matter concentrations with observations and with predicted future concentrations.

2. Modeling System

The modeling system used for this study is comprised of a global climate model (GCM) linked to regional-scale climate and air quality models. Each component of this modeling system is briefly described below.

2.1. Climatological meteorology

The GCM used is derived from the GISS 2' model as described by Mickley et al. (2004), coupled to the Harvard tropospheric ozone-NOx model as in Mickley et al. (1999). The GCM has a horizontal resolution of 4° latitude and 5° longitude and nine vertical layers in a sigma coordinate system extending from the surface to 10 hPa. The global climate simulation covers the period 1950–2055, with greenhouse gas concentrations updated annually using observations for 1950–2000 (Hansen et al., 2002) and the A1B scenario from the IPCC for 2000–2055 (IPCC, 2000). The radiation scheme assumes present-day climatological values for ozone and aerosol concentrations and has no feedbacks due to future pollutant concentration changes.

A regional climate model based on the Penn State/NCAR Mesoscale Model (MM5) was used to downscale the GCM outputs to a 36 km grid for 1995–2005 and for 2045–2055 (Leung and Gustafson, 2005). Lateral boundary conditions from the GCM outputs were applied at 6 hours intervals without assimilation of observational data. The regional climate model outputs were archived hourly and used to provide meteorological conditions for both emissions and air quality models.

2.2. Emissions

The Sparse Matrix Operator Kernel Emissions (SMOKE) modeling system was used to prepare emissions inputs consistent with the simulated meteorology, as both evaporative emissions and plume rise are functions of temperature. Meteorologically-driven biogenic emissions were computed using the Biogenic Emissions Inventory System (BEIS; Hanna et al., 2005). Three five-year sets of daily emissions inputs were prepared, as listed in Table 1. In the first set,

Table 1 Description of air quality simulations.

Simulation name	Modeling period	Anthropogenic emissions
CURR	1999–2003	2001
FUT1	2048–2052	2001
FUT2	2048–2052	2050

CURR, anthropogenic emissions were based on the U.S. Environmental Protection Agency National Emission Inventory for 2001, modulated by the climatology

simulated for the current period, and were merged with biogenic emissions computed using the same simulated current climatology. For the second set, FUT1, the same underlying anthropogenic emissions were used, though they were modulated by the simulated future climatology and merged with biogenic emissions computed for that future period. For the third set, FUT2, the same biogenic emissions were used as in FUT1, but anthropogenic emissions were scaled according to the A1B 2050 projections by the Asian Pacific Integrated Model (AIM) for the developed world (see Table 2).

Table 2 Scaling factors applied for all anthropogenic emission sectors in simulation FUT2, relative to FUT1.

Species	Factor
NOx	0.52
SO_2	0.37
VOCs	0.79
CO	1.5
PM	1
NH_3	1

2.3. Air quality simulations

Air quality simulations were performed with the Community Multiscale Air Quality (CMAQ) model (Byun and Schere, 2006) version 4.5. A continuous five-year CMAQ simulation was run for each of the three emissions scenarios listed in Table 1. Chemical boundary conditions for ozone, NOx, and related VOCs were taken from monthly averaged outputs of the Harvard tropospheric chemistry module coupled to the GISS GCM. For each time period, mean aerosol boundary conditions were computed from outputs of a related simulation conducted with the modeling system of Liao et al. (2003).

3. Results and Discussion

3.1. Current period evaluation

Total mass and speciated 24-hour measurements of $PM_{2.5}$ concentrations are collected every third day at sites in the Interagency Monitoring of Protected Visual Environments network (IMPROVE; see http://vista.cira.colostate.edu/improve). Summer and winter differences between modeled (CURR) average $PM_{2.5}$ concentrations and 2000–2004 observations are shown in Figure 1. For the summer, modeled concentrations at sites in the Pacific Northwest and in the central U.S. are positively biased by 2–6 $\mu g\ m^{-3}$, while most sites in the northeast exhibit an equivalent negative bias. For the winter, however, positive biases exist at nearly every site, exceeding 6 $\mu g\ m^{-3}$ at most sites in the central and eastern U.S.

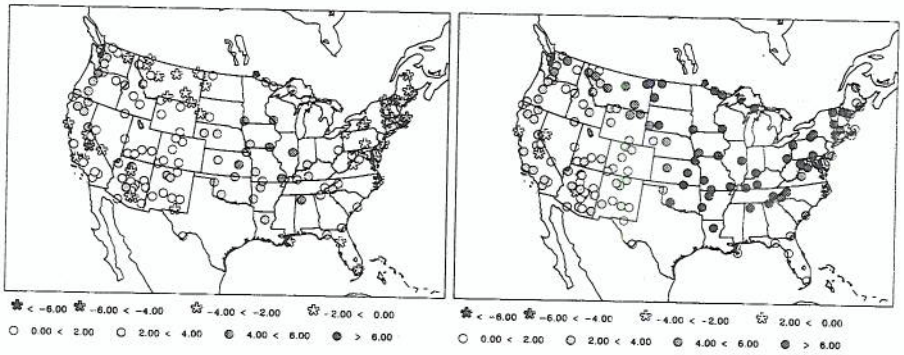

Fig. 1 Differences between average modeled $PM_{2.5}$ concentrations and measurements at IMPROVE monitoring sites for summer (left) and winter (right)

Similarly, difference plots between modeled and measured sulfate concentrations are shown in Figure 2. During the summer, predicted sulfate concentrations exhibit a positive bias greater than 1.5 μg m^{-3} in much of the central U.S. and somewhat weaker negative biases in the northeast and in California. During the winter, sulfate predictions are unbiased (within 0.5 μg m^{-3}) at most monitoring sites.

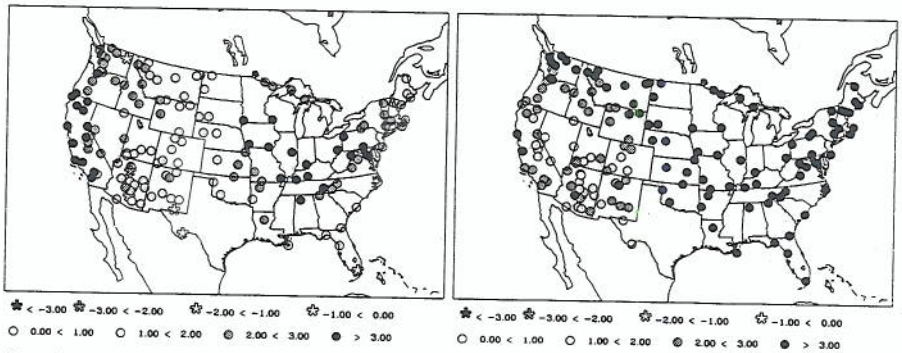

Fig. 2 Differences between average modeled sulfate concentrations and measurements at IMPROVE monitoring sites for summer (left) and winter (right)

Measured "soil" concentrations (a derived quantity based on measurements of certain trace elements) and modeled "other unspeciated PM" concentrations are shown in Figure 3. During both summer and winter, a large positive bias in modeled "other PM" concentrations is evident at nearly every monitoring site, making it the largest contributor to the errors in total $PM_{2.5}$. Preliminary investigations into this bias suggests that it is due to unrealistically high levels of dust (summer average 2 μg m^{-3}; winter average 8 μg m^{-3}) in the global model coming into the CMAQ modeling domain via the northern boundary.

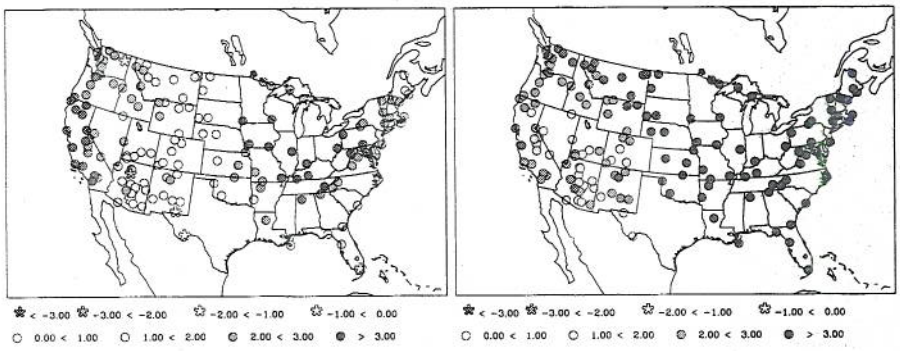

Fig. 3 Differences between average modeled "soil" concentrations and measurements at IMPROVE monitoring sites for summer (left) and winter (right)

3.2. Current-future differences

Differences between the average $PM_{2.5}$ concentrations for the two future period simulations and the CURR simulation are shown in Figure 4. For FUT1, summer average $PM_{2.5}$ concentrations decrease by 1–3 μg m^{-3} throughout most of the central and eastern U.S. and in California. In the winter, $PM_{2.5}$ decreases by 2–5 μg m^{-3} in the northern part of the domain. The decrease is even more substantial for the A1B-scaled emissions case FUT2, with average decreases from 3 to 9 μg m^{-3} in the eastern third of the U.S during both summer and winter.

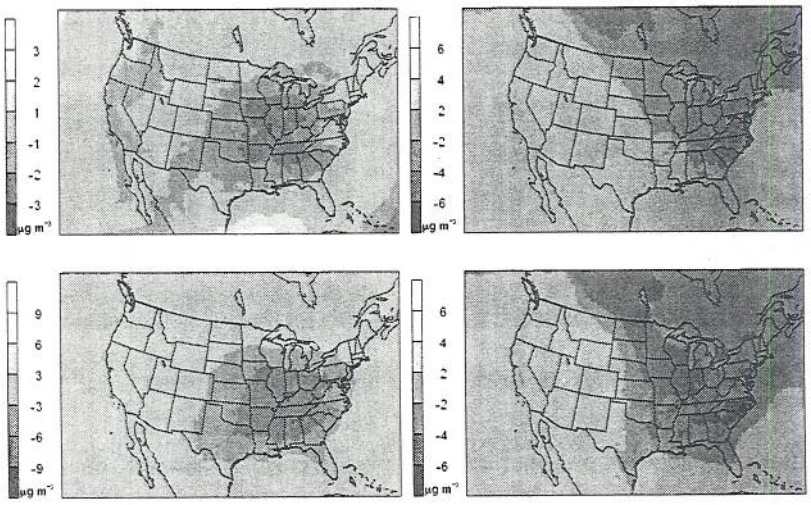

Fig. 4 Changes from CURR in five-year-average summer (left) and winter (right) $PM_{2.5}$ concentrations for FUT1 (top) and FUT2 (bottom)

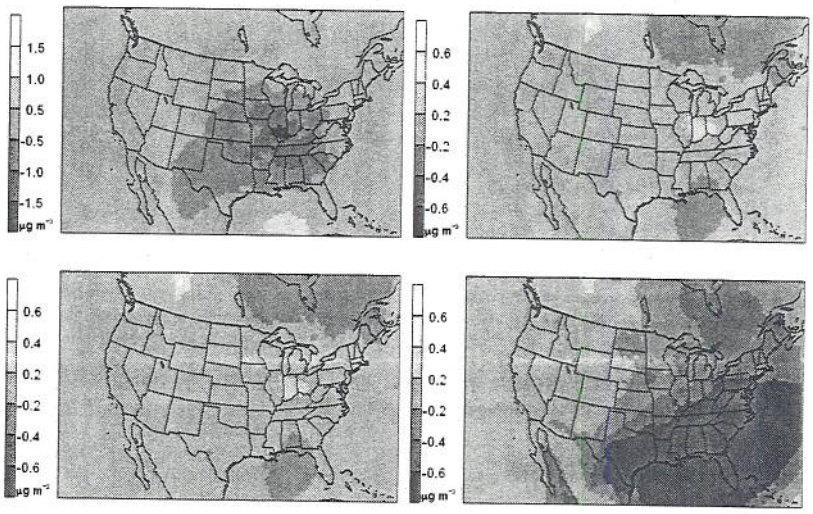

Fig. 5 Changes from CURR in five-year-average summer (left) and winter (right) sulfate concentrations for FUT1 (top) and FUT2 (bottom)

Differences between average sulfate concentrations for the two future period simulations and the CURR simulation are shown in Figure 5. For FUT1, summer average sulfate concentrations decrease by 0.5–1.5 μg m^{-3} throughout most of the central and southern U.S., while there is a slight increase of 0.2–0.4 μg m^{-3} in a portion of the Midwest. The decrease is larger for the A1B-scaled emissions case FUT2, with average sulfate decreases from 3 to 5 μg m^{-3} in the eastern third of the U.S during summer and 1–2 μg m^{-3} during the winter.

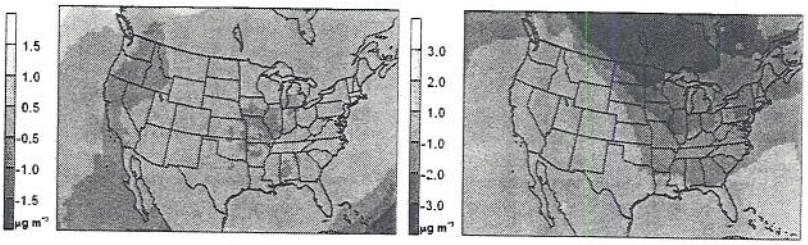

Fig. 6 Changes from CURR in five-year-average summer (left) and winter (right) "other PM" concentrations for FUT1

Differences between the summer and winter average "other PM" concentration for FUT1 and CURR simulation are shown in Figure 6. Dust emissions and boundary conditions were the same for FUT2 as for FUT1, so FUT2 "other PM" concentrations are virtually identical to those for FUT1 and are not shown. Relative to CURR, future summer average "other PM" concentrations decrease by 0.5–1.0 μg m^{-3} in the western U.S. and in parts of the central U.S., while large decreases exceeding 2 μg m^{-3} are evident during the winter. Since "other PM" is a chemically

inert species in CMAQ, the large decrease in future concentrations is due to changes in boundary conditions from the global model; these were unrealistically high for the current period as noted in Section 3.1.

4. Summary

Three sets of five-year air quality simulations for the continental U.S. have been conducted using downscaled meteorology and chemical boundary conditions from a global climate model. Model predictions for current period $PM_{2.5}$ concentrations are in reasonable agreement with recent observations, with the error dominated by overpredictions in dust concentrations from the global model. Comparison of model results for the current period with those for the future period with current anthropogenic emissions shows decreases in sulfate of 0.5–1.5 $\mu g\ m^{-3}$ during the summer, while summer sulfate concentrations decrease 3–5 $\mu g\ m^{-3}$ in the reduced emissions case. Future work for this study will explore the relative impact of changing meteorological variables and changes in chemical boundary conditions on $PM_{2.5}$ concentrations. A coupled climate and air quality model is under development, which will integrate feedbacks from pollutants on radiative forcing to better understand the relationships between climate change and air quality.

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Discussion

J. Baldasano:

What were the reasons why you chose the year 2050?

C. Nolte:

This study is part of a group of studies investigating the impact of future climate change on air quality. One of the reasons for agreeing on a common time period among these studies is to provide an ensemble of air quality projections. The year 2050 was chosen based on consensus of several groups. Climate signals at 2030 could be too small to detect within interannual variability. Climate modelers preferred 2100 for the same reason, but emission scenarios for 2100 are so uncertain as to be untenable. Hence, 2050 was a good compromise.

P. Kishcha:

Were future land use changes considered in the model predictions under discussion?

C. Nolte:

No. Future land use categories were assumed to be unchanged. This represents an important uncertainty in our modeling system.

A. Aulinger:

Did you compute statistics on peak concentrations of PM and O_3 in order to assess the number of days with increased health risks due to climate change or changes in precursor concentrations?

C. Nolte:

Yes. We have computed the number of days per year at each site where the maximum 8-hour average ozone and $PM_{2.5}$ exceeded threshold values of 80 ppb and 35 $\mu g\ m^{-3}$. The spatial pattern of change in the number of exceedances generally follows the pattern of the changes in the means. However, our ozone concentration predictions under current climate conditions are positively biased by 10–15 ppb in parts of the U.S., which hinders our ability to predict with accuracy exceedances above a given threshold.