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Atmospheric
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Discussions

Interactive comment on "Quantification of impact of climate uncertainty on regional air quality" *by* K.-J. Liao et al.

K.-J. Liao et al.

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The paper attempts to estimate the uncertainty of the effects of future climate change on air quality in the US. This is an interesting question both methodologically and also from a policy design point of view. The authors choose one future emissions scenario (the IPCC A1B), one GCM (the GISS) and rely on a single set of simulations for 2050. These choices limit severely both the potential uncertainty and variability in the problem. The authors introduce an original approach (at least in this air quality context) for the development of extreme meteorological scenarios. While this is a rather limited quantification of the impact of climate uncertainty on air quality in the US, the paper still makes a significant contribution to the problem of future air quality in a changing climate. However, the methodology needs to be presented clearly and the limitations of both the methods and the conclusions should be analyzed.

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Reply: We would like to thank the reviewer for providing detailed reviews and positive comments made. The methodology used in this study has been extended and more detailed description with regard to the methodology has been added in the revised manuscript. Furthermore, the results of this study have been discussed in detail and more implications haven been provided. The point-by-point page response details how we have addressed each comment and how the manuscript has been modified. Please see replies below for detailed responses to the comments.

Major issues:

(1) The authors have chosen as a basis for their uncertainty estimation the IPCC A1B scenario. Some discussion of the dependence of their results (taking into account both the global climate and US emission changes) on this choice is necessary.

Reply: First of all, we have included more discussion of the reasons for choosing the IPCC A1B scenario as the base case climate in Section 2.1 as follows: The IPCC A1B emission scenario assumes a future world of very rapid economic growth with a balanced case between fossil and non-fossil energy sources and projects mid-level increases in greenhouse gas emissions and temperatures (Nakicenovic, 2000). As such, the IPCC A1B is used for the base case GISS-MM5 simulations within multiple IPCC scenarios. Also, we have added two equations (2.1 & 2.2) in Section 2.1 to show that the simulated uncertainties induced by the extreme climate scenarios do not depend on the emission scenario used for the base case (i.e., IPCC A1B). We also mention that the differences between the extreme and base case scenarios only depend on probabilistic distributions from the IGSM outputs. Moreover, we have added discussion regarding using both global emission trends and projections of regional anthropogenic precursor emissions (i.e., U.S. Clean Air Interstate Rule (CAIR)) in Section 2.2 as follows: The IPCC A1B emission scenario projects decreases in SO2, NOx and non-methane volatile organic compound (NMVOC) emissions from Organization for Economic Co-operation and Development (OECD) countries, including the U.S. and Canada, in 2050s as compared with 1990s based on long-term energy-use and

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economic trends, which do not include currently planned precursor emission control regulations (Nakicenovic, 2000). For future regional air quality modeling, projections in regional anthropogenic precursor emission changes are required in addition to national and global emission trends. In this study, projections of regional anthropogenic precursor emissions were developed for North America integrating currently planned emission controls (i.e., U.S. Clean Air Interstate Rule (CAIR) (Houyoux, 2004)) and long-term economic and population growth, based on the A1B scenario.

(2) The paper is based on the simulation of a single year (more precisely a few months in a single year). Given the variability of meteorology these results can be misleading even if the objective is just the calculation of the uncertainty. Some additional analysis is necessary to address this point.

Reply: The concern is understandable. Here, we refer back to a foundational paper (Tagaris et al, JGR, 2007) to discuss interannual variability of meteorology. A discussion has been added in Section 2.2 of the revised manuscript as follows: Interannual variability of meteorology is a critical issue since only the year 2050 is chosen as the future episode examined in this study. The analysis for the interannual variability of climate fields has been presented by Tagaris et al. (2007): the results show that cumulative distribution function (CDF) and spatial distribution plots for temperature and absolute humidity are similar for the three consecutive future years (2049-2051). The former paper provides information on interannual variability, and this paper looks at perturbations to the modeled base meteorologies.

(3) I think that the technique used for the estimation of the uncertainty is one of the major contributions of the paper and should be described in more detail. Unfortunately, even the additional information in the Supplementary Material is not sufficient. It is not clear how the authors calculate the different percentiles of the three-dimensional (y, z, m) fields. Also how do they deal with both the temperature and relative humidity fields? What do they do with the rest of the meteorological variables? Last but not least, it is not clear (at least to me) what exactly do these extreme meteorological fields capture

and what they do not capture? For example, do they include the possibility of very wet summers or winters in a specific region? How about major changes in mixing heights?

Reply: First of all, description of development of the probabilistic distributions of two-dimensional climate fields in IGSM has been in Section 2.1 as follows: The probability distribution of temperature and humidity changes in 2050 were derived from a set of 1000 ensemble simulations (Webster et al., 2003). In configuring this ensemble of simulations, the model uncertainty is included by using a joint PDF of three climate model parameters, i.e., climate sensitivity, ocean heat uptake, and aerosol radiative forcing along with PDF of predicted anthropogenic emissions of major greenhouse gases which is calculated using Monte Carlo analysis of the EPPA model. Second, the method of constructing high- and low-extreme climate scenarios using the three percentiles of IGSM climate fields and base case GISS-MM5 has been extended and moved from Supplementary Material to Section 2.1. Step-by-step description has been added to provide readers more clear ideas how the works have been done. Specifically, in Section 2.1,we have added: Climate fields used are associated with the 0.5th, 50th and 99.5th percentiles of temperature and absolute humidity from IGSM. The 50th percentile of both the meteorological parameters are adjusted to the GISS-MM5 by minimizing the discrepancies in temporal and spatial resolutions between the 50th IGSM and GISS-MM5 outputs and used to develop perturbation fields along with the GISS-MM5 based on the following processes: A three-dimensional time-dependent variable of the GISS-MM5 climate is decomposed into a spatially (longitudonally) and temporally (monthly) averaged field and a fluctuating term. Then the longitudinally and monthly-averaged term is replaced with the 0.5th, 50th and 99.5th percentiles of meteorological fields from the IGSM results and used to construct intermediate three-dimensional climate fields along with the fluctuating term. The new three-dimensional time-dependent fields for the three IGSM percentiles are derived after re-running MM5 with new boundary conditions from the intermediate climate in order to get conservative meteorological fields. We keep the GISS-MM5 field as the base case scenario in order to compare with current pollutant levels (note that new fields of the IGSM

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50th percentile climate are not identical to the GISS-MM5 fields). The high- and low-extreme fields are calculated as equations 2.1 & 2.2. Third, as mentioned in Section 2.1, changes in other meteorological fields (e.g., precipitation, mixing height, wind fields, etc.) are dynamically consistent with perturbations in temperature and absolute humidity since we have re-run MM5 in order to get conservative meteorological fields. Fourth, we do not examine what will happen under very extreme cases by arbitrarily changing the meteorological fields (i.e., a very wet year or major changes in mixing height). The changes in all meteorological fields are driven by perturbations in temperature and absolute humidity resulting from global climate simulations. In our analysis, the extreme meteorological fields capture a very wide range of the likely changes in meteorology based on the extreme percentiles of probabilistic distributions of temperature and absolute humidity changes in 2050. For example, in Section 3.1, we have added discussion as follows: The differences in precipitation between the 2050 base case and extreme scenarios are driven by the perturbations in temperatures and absolute humidity and based on the extreme percentiles of probabilistic distributions of temperature and absolute humidity changes derived from global modeling in 2050.

(4) Is the difference between the PM and ozone sensitivities just due to the respective averaging periods (8-hr versus annual average)? Some analysis of the sensitivity of the daily maxima PM concentrations would be quite helpful, especially considering the tightening of the daily average PM2.5 standard in the U.S.

Reply: We use 4th-highest daily maximum ozone and annualized daily PM2.5 for sensitivity analysis presented in Section 4 in order to be consistent with the NAAQS as mentioned in Section 2.2. Moreover, in addition to annualized PM2.5 levels, we have added a new table (Table 4) which includes annualized monthly maximum daily PM2.5 concentrations and their sensitivities to SO2, anthropogenic NOx and VOC emissions in order to examine how extreme climate scenarios influence peak PM2.5 levels in urban areas and effectiveness of control strategies. The associated discussion is added in Section 4 as follows: Annualized monthly maximum daily PM2.5 lev-

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els (average of monthly maximum daily PM2.5 for January, April, July and October) and their sensitivities are also examined in 2050 for five U.S. urban areas, Atlanta, Chicago, Houston, Los Angeles and New York, where currently have high PM2.5 levels (http://www.epa.gov/oar/oaqps/greenbk/, last access: 07/18/2008). Such areas are particularly susceptible to the climate penalty, especially when tightening of future daily average PM2.5 standards is considered. For the five cities examined, sensitivities of annualized monthly maximum daily PM2.5 to anthropogenic NOx emissions are predicted to be affected by the extreme climate scenarios since ammonium nitrate (NH4NO3) formation is quite sensitive to changes in meteorology (e.g. temperature). Responses of annualized monthly maximum daily PM2.5 to SO2 emissions are also predicted to be different under the extreme climate scenarios in Chicago due to high SO2 emissions in the Midwest region of the U.S. (Table 4). For four of the five cities examined, Los Angeles being the exception, reductions in SO2 and anthropogenic NOx emissions are predicted to continue to be effective for decreasing annualized monthly peak daily PM2.5 levels under the extreme climate scenarios in 2050. While reductions in anthropogenic NOx and VOCs emissions are predicted to be effective for decreasing annualized monthly peak PM2.5 levels in Los Angeles for the three climate scenarios in 2050. Overall, the results for the five cities show that, although the effectiveness of emission controls for decreasing peak PM2.5 levels responds to the extreme climate scenarios, the directions of currently planned emission controls will not be significantly affected.

(5) Change in regional precipitation is always one of the most uncertain variables in such modeling exercises. How do the current predictions compare to others in the literature? How extreme are the extreme scenarios?

Reply: The 2001 and the 2050 base meteorological fields used here have been published by Leung and Gustafson (2005, GRL), and that work included extensive analysis, along with the analysis presented by Tagaris et al. (2007). The precipitation downscaled from the base case simulation, GISS-MM5, have been compared with observations and shown good agreements in seasonal cycle and regional variation for the episode of 1995-2005 (Leung and Gustafson, Potential regional climate change and implications to US air quality, Geophysical Research Letters, 2005). In this work we focus on the impact of uncertainties in meteorology derived from temperature and absolute humidity on regional air quality. The changes in precipitation under the extreme climate scenarios for the projections used in this study are presented in Figure 4.

(6) The extreme scenario appears to result in predictions of both increases and decreases in 4th MDA-8hr ozone. Are all the major urban areas characterized by increases? Is this uniformity real or just a consequence of how this extreme scenario was constructed?

Reply: The figure of spatial distribution of the changes in 4th MDA8hr ozone (Figure 6) shows that 4th MDA 8-hr ozone concentrations are predicted to increase in most of the more highly polluted urban areas (e.g., Chicago, Houston, New York, etc.) for the high-extreme scenario. As mentioned in Section 3.3, the extreme climate scenarios affect PAN decomposition and OH levels which influence ozone formation via NO/NO2 photochemical cycles. On the other hand, 4th MDA 8-hr ozone concentrations in some areas of the West region, where have VOC-saturated ozone formation scheme, are predicted to decrease for the high-extreme scenario. Therefore, we conclude that changes in 4th MDA 8-hr ozone are mainly attributed to effects of extreme climate scenario on photochemical reactions and precursor emissions. However, the patterns of changes in 4th MDA8hr ozone do not follow those of changes in meteorological fields (e.g., temperature (Fig. 2), absolute humidity (Fig. 3), precipitation (Fig 4), etc.) since changes in ozone are also affected by local emissions as well.

(7) The paper focuses on total PM2.5 changes and just mentions that these changes are dominated by sulfate and nitrate changes. Some additional information about the predicted changes in the major PM2.5 components (sulfate, nitrate, primary and secondary organics, and dust) is necessary.

Reply: In Table 3 of the revised manuscript, we have added seasonal variation of total PM2.5, sulfate, nitrate, primary and secondary organic aerosols for the five regions for the three extreme climate scenarios in 2050. The associated discussion is added in Section 3.4 as follows: The 1.0 μg m-3 decrease in annualized PM2.5 levels in the Midwest for the high-extreme scenario is mainly due to lower sulfate and nitrate in the winter (January) compared with the base case (Table 3), while the 0.5 μg m-3 increase in annualized PM2.5 levels in the Southeast for the low-extreme scenario is due to higher nitrate in the winter (January) compared with the base case (Table 3). SOA is predicted to be influenced by changes in biogenic VOC emissions as well as modifications in the formation rates under the effects of the extreme climate scenarios. In CMAQ version 4.3, the SOA gas-particle partitioning model is based on the Secondary Organic Aerosol Model (SORGAM) (Schell et al., 2001), which does not account for SOA formation from isoprene. Some studies show that isoprene significantly contributes to SOA formation (Claeys et al., 2004), and SOA levels are predicted to be underestimated without including isoprene as a SOA precursor (Zhang et al., 2007;Morris et al., 2006;Pun and Seigneur, 2007).

(8) The paper concludes that the impact of climate uncertainties may be substantial in some urban areas. However, there is very little discussion of specific urban areas (and corresponding uncertainties) in the paper.

Reply: Good suggestion. In Section of 3.3 of the revised manuscript, the impacts of climate uncertainty on urban ozone are discussed as follows: When temperature-induced increases in VOC emissions (especially biogenic VOC emissions, up to ~29% regionally, Table 1 & Figure 5) are considered, higher ozone levels are found in NOx-saturated (or VOC-sensitive) urban areas, e.g., Chicago and New York, and the effects of the high-extreme climate scenario are predicted to be more significant. Moreover, for five urban areas in the continental U.S. (i.e., Atlanta, Chicago, Houston, New York and Los Angeles), our previous results show that concentrations of daily maximum 8-hr average ozone are predicted to positively respond to VOC emissions on some days for

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the base case GISS-MM5 simulations in 2050, especially in Chicago and New York, although ozone formation is predicted to be more NOx-limited in 2050 than 2001 due to currently planned emission controls (Liao et al., 2008).

Other Comments:

(9) Some additional information about the IGSM model is necessary (version number?). Also, how is the Emissions Predictions and Policy Analysis (EPPA) module used? Are its results consistent with those of the IPCC A1B scenario for the US?

Reply: First of all, the version of IGSM used in this study was the same as the one presented by Webster et al. (Uncertainty Analysis of Climate Change and Policy Response, Climate Change, 2003). A more detailed description for the MIT IGSM model has been added in Section 2.1: In this study, climate fields from MIT Integrated Global System Model (IGSM) (Prinn et al., 1999;Reilly et al., 1999) simulations, in the form of probabilistic distributions, are used to quantify uncertainties inherent in forecasts of future changes, and their associated effects on regional air quality. The IGSM includes components of: (a) the Emissions Prediction and Policy Analysis (EPPA) model, designed to project emissions of climate-relevant gases and the economic consequences of policies to limit them (Babiker et al., 2000), (b) the climate model, a 2D zonally-averaged land-ocean resolving atmospheric model, coupled to an atmospheric chemistry model, (c) a 2D ocean model consisting of a surface mixed layer with specified meridional heat transport, diffusion of temperature anomalies into the deep ocean, an ocean carbon component, and a thermodynamic sea-ice model (Sokolov and Stone, 1998;Holian et al., 2001;Wang et al., 1998), (d) the Terrestrial Ecosystem Model (TEM 4.1) (Melillo et al., 1993;Tian et al., 1999), designed to simulate carbon and nitrogen dynamics of terrestrial ecosystems, and (e) the Natural Emissions Model (NEM) that calculates natural terrestrial fluxes of CH4 and N2O from soils and wetlands (Prinn et al., 1999). The probability distribution of temperature and humidity changes in 2050 were derived from a set of 1000 ensemble simulations (Webster et al., 2003). In configuring this ensemble of simulations, the model uncertainty is included by using a joint

PDF of three climate model parameters, i.e., climate sensitivity, ocean heat uptake, and aerosol radiative forcing along with PDF of predicted anthropogenic emissions of major greenhouse gases which is calculated using Monte Carlo analysis of the EPPA model. Second, as mentioned in Section 2.1, the EPPA model is used to estimate uncertainties in anthropogenic emissions using the Monde Carlo method. In the framework of IGSM, EPPA results are applied to the climate model for ensemble simulations to drive probabilistic distributions of climate fields. Third, the IGSM has been specifically developed to study climate uncertainties quantitatively. The IGSM outputs show probabilistic distributions of climate changes and are not used for comparison with specific IPCC scenario.

(10) Abstract: Which areas are most responsive to climate change? Why?

Reply: Good suggestion. Now the text stands as: Impacts of the extreme climate scenarios on concentrations of summertime fourth-highest daily maximum 8-hour average ozone are predicted to be up to 10 ppbV (about one-seventh of the current NAAQS of ozone of 75 ppbV) in urban areas of the Northeast, Midwest and Texas due to impacts of meteorological changes, especially temperature and humidity, on the photochemistry of tropospheric ozone and increases in biogenic VOC emissions, though the differences in average peak ozone concentrations are about 1-2 ppbV on a regional basis.

(11) The table with the emissions in the supplement is not sufficient. The emissions of biogenic and anthropogenic VOCs as well as those of primary PM2.5 should be added to the table. Also a column with the current emissions would be helpful. Finally, the units (per grid) are rather confusing. How about just the emissions in the domain or subdomain per year?

Reply: Good suggestion. Annualized and summer-average emissions of biogenic and anthropogenic VOCs as well as elementary PM2.5 for 2001 and the three extreme climate scenarios in 2050 are added in Table S2 of the supplementary material. The daily

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average emissions of all species, including SO2, NOx, biogenic and anthropogenic VOCs as well as elementary carbon, are presented in tons per day for each subdomain as well as the continental U.S.

(12) The absolute humidity entries in Table 1 are confusing. They are all given in percent.

Reply: The subtitle of Table 1 has been changed from Absolute Humidity (%) to Absolute Humidity (g/Kg). All the values of Absolute Humidity in Table 1 are changed correspondently.

(13) Figure 3 is discussed before Figure 2. Their order should probably be switched.

Reply: We have complied with the reviewer suggestion (note that new Figures have been added).

Interactive comment on Atmos. Chem. Phys. Discuss., 8, 7781, 2008.