CLIMATE CHANGE AND OZONE AIR QUALITY: APPLICATIONS OF A COUPLED GCM/MM5/CMAQ MODELING SYSTEM

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1. INTRODUCTION

Photochemical models systems such as CMAQ (Byun and Ching, 1999) have been used to simulate ozone concentrations under present day meteorological conditions with either current emissions or emissions that reflect emission control policies. In recent years, there has been a growing interest in assessing the potential impact of climate change on air pollution and, ultimately, the public health impacts of both changing climate and air quality (McCarthy et al., 2001). Climate change can influence the concentration and distribution of air pollutants through a variety of direct and indirect processes, including the modification of biogenic emissions, the change of chemical reaction rates, mixed-layer heights that affect vertical mixing of pollutants, and modifications of synoptic flow patterns that govern pollutant transport. This paper gives an overview of the substantiation and applications of a modeling study for simulating the effects of global climate change on regional climate and air quality over the northeastern United States in order to project the associated public health impacts in the region. A more detailed description and analysis is given in Hogrefe et al. (2003a,b). A unique feature of this study is the linking of a regional mesoscale model (MM5) with a global climate model. The meteorological outputs from the mesoscale model simulations are subsequently used to simulate air quality by CMAQ. Finally, results from these air quality-modeling simulations are coupled to health impact models. The health impact results will be presented in future works.

2. MODEL DESCRIPTION AND DATA BASE

2.1 Emissions processing

Emissions are the driving force for climate change (through an increase in greenhouse gas emissions) and are also a critical input to the air quality model. The IPCC SRES (IPCC, 2000) has generated various future emissions scenarios based on projections of population, technology change, economic growth, etc. In this paper, we use the SRES “A2” scenario. This scenario is characterized by a large increase of CO_2 emissions, relatively weak environmental concerns, and large population increases (15 billion by 2100). The greenhouse gas emissions from this scenario are used as inputs to the global and regional climate models described below. Because the SRES emission scenarios are global in nature, their spatial resolution is not adequate for regional air quality modeling. Therefore, we use the county-level EPA 1996 National Emissions Trends (NET96) inventory as basis for air quality modeling. This emission inventory is processed by the Sparse Matrix Operator Kernel Emissions Modeling System (SMOKE) (Carolina Environmental Programs, 2003) to obtain gridded, hourly, speciated emission inputs for the air quality model. Future year emissions are estimated by multiplying the base year pollutant inventory with the spatially-uniform growth factors for the SRES “A2” scenario. For many industrialized countries including the U.S., “A2” VOC emissions are estimated to increase by 8% and NO_x emissions by 29.5% by the 2050s relative to the 1990s.

2.2 Global and regional climate modeling

Meteorological fields for the air quality simulations were obtained by coupling the MM5 mesoscale model (Grell, 1994) to the Goddard Institute for Space Studies (GISS) 4ºx5º resolution Global Atmosphere-Ocean Model (GISS-GCM) (Russell et al., 1995). Details on the setup of this modeling system are described in Lynn et al. (2003a,b). MM5 simulations driven by GISS-GCM through boundary and initial condition inputs were performed for the summer seasons (June – August) from 1993 – 1997 and 2053 – 2057. The MM5 was applied in a nested-grid mode with an inner grid having a horizontal resolution of 36 km over the eastern U.S. and an outer grid having a horizontal resolution of 108 km covering most of the continental U.S.; only results from the 36 km simulation were used for CMAQ simulations. The MM5 had 35 vertical layers, the height of the first layer was approximately 70 meters. Lynn et al. (2003a) tested several different combinations of MM5 physics options, in this study we selected the MM5 simulations that were performed with the MRF boundary layer scheme (Hong and Pan, 1996), the Betts-Miller cloud scheme (Betts, 1986) and the RRTM radiation scheme (Mlawer et al., 1997).

2.3 Air Quality modeling

Using the SMOKE-processed emissions and the 36 km MM5 regional climate simulation for the five summer seasons in the years 1993 – 1997 and 2053 - 2057, air quality simulations were performed using the Community Multiscale Air Quality (CMAQ) model (Byun and Ching, 1999). The modeling domain consists of 68

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x 59 horizontal and 16 vertical grid cells. The Carbon Bond IV Mechanism (CB-IV) (Gery et al., 1989) was used to simulate gas phase chemistry, no aerosol concentrations were simulated, and time-invariant climatological profiles for ozone and its precursors were used as boundary conditions.

2.4 Observations

Hourly surface observations of meteorological variables were retrieved from the Data Support Section at the National Center for Atmospheric Research (NCAR-DSS). There were 258 monitors in the entire modeling domain that have at least 75% non-missing temperature observations for each of the summers from 1993-1997. Additionally, we obtained hourly surface ozone observations for 1993 – 1997 from the EPA's AIRS system for 428 monitors located in the modeling domain.

3. RESULTS AND DISCUSSION

3.1 Regional climate modeling

Because of their effects on biogenic emissions and chemical reactions rates, it is important to evaluate temperature predictions from MM5. A detailed evaluation of both mean spatial fields as well as observed and predicted temperature variability is presented in Lynn et al. (2003a,b) and Hogrefe et al. (2003a). In this short overview paper, Figure 1 illustrates an example of their findings. The panels in Figure 2 show the observed and predicted daily maximum temperature, averaged over June 1- August 31 for the five years simulated in the 1990s. In addition, differences between observed and predicted values are presented. It can be seen that MM5 captures the latitudinal gradients of average daily maximum temperatures, but it is also obvious that daily maximum values are generally underestimated in the northern part of the modeling domain, while they are overestimated in the southern portion of the modeling domain. Lynn et al. (2003a,b) discussed the sensitivity of model-predicted values to the parameterization of different physics options in MM5, namely the treatment of boundary layer physics, cumulus cloud parameterization, and radiation scheme. Hogrefe et al. (2003a) concluded that – while model biases do exist at some locations - MM5 generally re-produces spatial and temporal variability on the synoptic and longer-term time scales; this had not been the case for the GCM simulations driving MM5. Furthermore, they illustrated that MM5 captures the frequency distribution of the duration of extreme heat events, a result that is important for the use of MM5 and CMAQ predictions for future health impact analysis.

Next, an example of the MM5-predicted future regional climate under the SRES "A2" scenario is presented in Figure 2. The three panels show the summertime-average daily maximum temperature for the five summers calculated for 1993 – 1997 and 2053-2057 as well as their differences. It can be seen that MM5 predicts an increase of average summertime daily maximum temperatures of 1.5ºC to 3.5ºC for most regions in the modeling domain. As discussed by Lynn et al. (2003a,b), the MM5-predicted climate change - while generally consistent with the one predicted by the GCM - shows finer scale features as well as quantitative regional-scale differences when compared to the GCM-predicted changes, resulting from higher grid resolution and a different treatment of model physics.

3.2. Air quality modeling

A map of observed and predicted daily maximum 1-hr ozone concentrations averaged over all simulated days during the years 1993-1997 was constructed and is presented in Figure 3. It can be seen that the spatial pattern of mean daily maximum ozone concentrations is captured rather well. The correlation coefficient R between the observed and predicted average daily maximum ozone concentrations at all 428 stations is 0.68. Bands of high average ozone concentrations are observed and predicted along the Ohio River valley and in an area stretching from northern Alabama and Georgia to central North Carolina and along the eastern seaboard. CMAQ slightly underestimates mean daily maximum ozone concentrations in the greater New York City metropolitan area. The spatial extent of mean ozone concentrations in excess of 55 ppb is also captured well. Furthermore, Hogrefe et al. (2003a) presented results indicating that the CMAQ simulations for the five summers in the 1990s are able to capture the regional-scale ozone climatology and longer-term fluctuations and speculated that increased horizontal and vertical grid resolution presumably would be necessary to better represent the entire range of meteorological and ozone fluctuations on shorter time scales, especially in urban areas.

Analysis of the MM5 daily maximum temperature fields presented above showed an increase of 1.5ºC to 3.5ºC from the 1990s to the 2050s. Along with changes in other meteorological variables and flow patterns, these changes are expected to have a profound impact on predicted ozone concentrations through changes of chemical reaction rates and biogenic emissions. Furthermore, the SRES "A2" scenario used in this study is characterized by an increase of VOC and NO_x emissions as discussed above. To examine the isolated and combined effects of changing climate (including changing biogenic emission) and changing anthropogenic emissions of ozone precursors, four sets of five-summer CMAQ simulations were performed with all possible combinations of current and future climate and emissions. Average summertime daily maximum 1-hr ozone concentrations from these four sets of simulations are presented in Figure 4. It can be seen that changes in climate alone (including changes in temperature-sensitive biogenic emissions) cause ozone increases of similar magnitude as the "A2" increases in anthropogenic ozone precursor emissions. The largest ozone concentrations are predicted in the simulation with both future climate and future "A2" ozone precursor emissions. A more detailed analysis of these simulations and results from the factor analysis technique are presented in Hogrefe et al. (2003b).

4. SUMMARY

This paper provided an overview of a modeling study to simulate the effects of climate change on air quality. Results indicate that the GCM/MM5/CMAQ system is a suitable tool for the simulation of summertime meteorological and air quality conditions over the eastern U.S. in the present climate. The results also indicate that the predicted changes in anthropogenic emissions and the changes in regional climate such as temperature, vertical mixing, and synoptic flow patterns both contribute to a deterioration of future air quality.

5. ACKNOWLEDGMENTS

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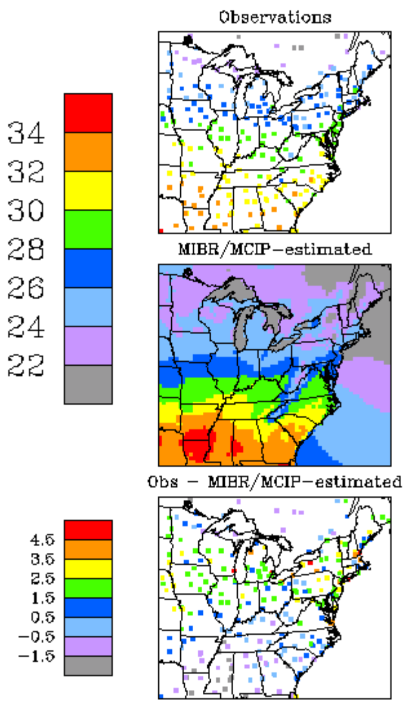

Figure 1: Daily maximum temperature, averaged over all summer days 1993 – 1997, for observations (top) and MM5 predictions (center). The bottom panel shows differences between observed and MM5-predicted average daily maximum temperatures.

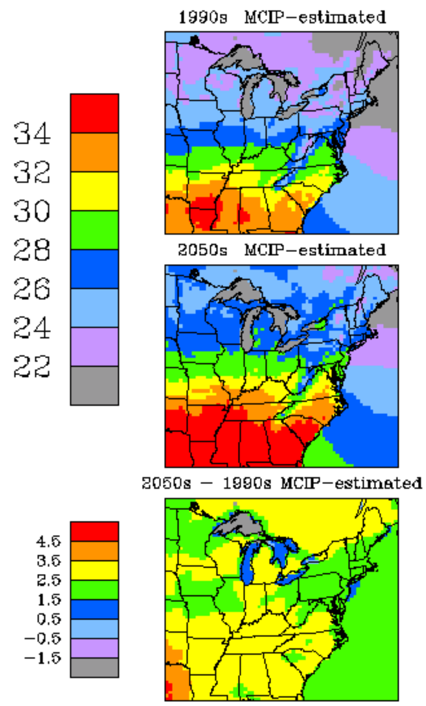

Figure 2: MM5-predicted daily maximum temperature, averaged over all summer days. 1993 – 1997 (top), 2053 – 2057 (center), and 2050s minus 1990s (bottom).

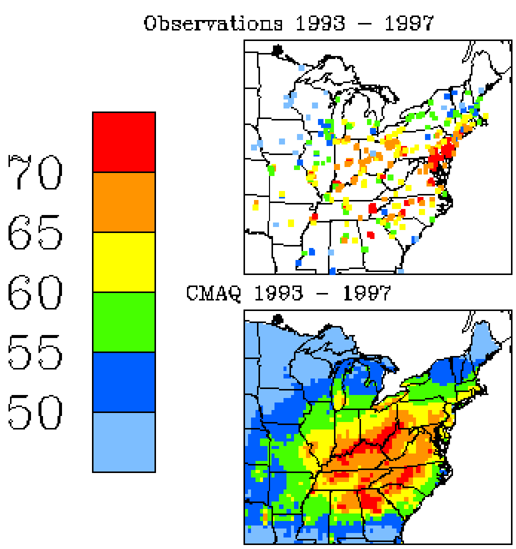

Figure 3: Daily maximum 1-hr ozone concentrations, averaged over all summer days 1993 – 1997, for observations (top) and CMAQ predictions (bottom).

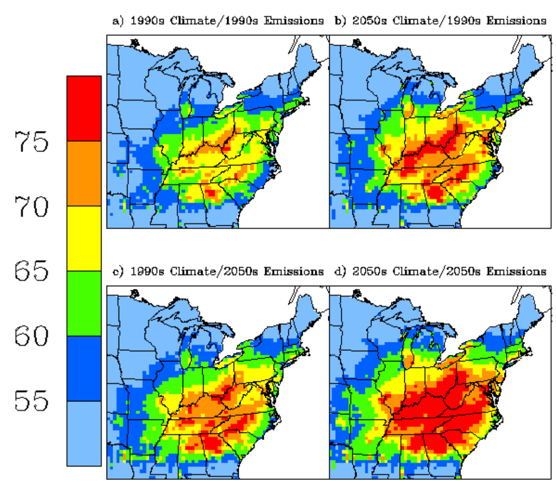

Figure 4: CMAQ-predicted daily maximum 1-hr ozone concentrations, averaged over all summer days. 1990s climate with 1990s anthropogenic emissions (upper left), 2050s climate with 1990s anthropogenic emissions (upper right), 1990s climate with 2050s anthropogenic emissions (lower left), and 2050s climate with 2050s anthropogenic emissions (lower right).