Chapter 9 –Session 4 Overview: Climate Change and Air Quality Interactions

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Session 4 Overview: Climate Change and Air Quality Interactions

9.0 Introduction

The Atmospheric Modeling and Analysis Division's (AMAD) climate-related research began in 2002 as a collaborative project on the potential impacts of future climate on air quality. Five Labs and Centers within the EPA Office of Research and Development (ORD) are involved including the National Center for Environmental Assessment, National Risk Management Research Laboratory, National Center for Environmental Research, and National Exposure Research Laboratory. This project was developed to support the ORD Global Research Program's Long Term Goal 2 effort: Assessment of the impacts of global change on air quality. The EPA National Center for Environmental Assessment (NCEA) had responsibility for coordinating this assessment, and AMAD's modeling scenarios directly contributed to the 2008 interim assessment report.

While the modeling studies were underway for this assessment of climate impacts on air quality, several events have occurred that heighten the climate-related needs of the USEPA Program Offices and Regions. With the 2007 Supreme Court ruling (*Massachusetts vs. EPA*) that EPA has jurisdiction under the Clean Air Act (CAA) to regulate greenhouse gases, the EPA Office of Air and Radiation is now grappling with how to incorporate climate into decision-making tools for air quality management. Traditionally, air quality control scenarios were developed using regional scale meteorology and air quality models, without consideration of future climate. The findings from AMAD's air quality and climate study demonstrate that both climate variability and trends can reduce the effectiveness of air quality control efforts. "Climate penalty" has become a common term describing this issue where additional controls may need to be considered in order to comply with the National Ambient Air Quality Standards in the future. In addition to how air quality decision-making tools may need to account for the potential risk of a "climate penalty," the Program Offices are also recognizing that air quality changes can also impact climate trends positively or negatively since many air pollutants such as sulfate, ozone, and black carbon are radiatively active. Having modeling tools that include the impact of air quality changes on the radiative budget and climate trends are also needed to develop integrated air quality and climate management strategies.

In light of these needs, since the Supreme Court ruling, Congress injected substantial new funds into the ORD to prepare and support the Agency's efforts to regulate emissions of greenhouse gases. AMAD received approximately one-third of these omnibus funds to advance regional air quality and climate modeling tools and complete new air quality modeling under greenhouse gas (GHG) emission control and mobile fuel scenarios. The EPA Advanced Notice of Proposed Rulemaking (ANPR) was released in July 2008, and described how GHG control policies would be implemented under the authority of the CAA. While it is still uncertain at this time whether GHG emission controls would be implemented under the CAA or new legislation, the ANPR clearly demonstrates that atmospheric modeling tools that can incorporate climate and air quality interactions (i.e., both climate impacts on air quality and climate effects from air quality changes) will be needed in the near future once EPA's responsibilities expand to protect human health and the environment from a changing climate.

The research presented here demonstrates what has been learned from AMAD's pilot study on regional air quality impacts from future climate, the extended contributions from this project through partnerships and collaborations, and the new efforts underway to advance the modeling tools for EPA's Program and Regional Offices. This is a transitional time where one project is expanding into a program that will develop modeling tools to better address climate impacts on the environment for both air quality and water quality management.

9.1 Research Summary

Air quality is known to be highly sensitive to meteorological conditions, including temperature, precipitation frequency, and the assimilative capacity of the atmosphere. Air quality management plans have traditionally been developed using one year (or less) of recent meteorology, yet emissions controls are implemented over several decades. Climate change could potentially affect the efficacy of emissions control strategies designed to meet the National Ambient Air Quality Standards.

AMAD developed a pilot modeling project in 2002, referred to as the Climate Impacts on Regional Air Quality or CIRAQ project, in collaboration with other ORD partners to investigate how future climate could affect air quality conditions. The first milestone for this project was a 2008 interim assessment report on the impacts of future climate on ozone (O_3). Primarily through support from the NCER climate and air quality grant program, AMAD developed linkages with global scale climate and chemistry models and regional climate scenarios via downscaling. The modeling approach was to separate climate effects from future emission changes, since future emissions are both very uncertain and likely to have substantial impacts on the air quality. While anthropogenic emissions were maintained at current levels, a regional climate scenario was used for current and future (ca. 2050) using the Mesoscale Meteorology model version 5 (MM5) and the NASA Goddard Institute for Space Studies (GISS) II' global climate model (GCM). The GISS II' GCM simulations were developed under the Intergovernmental Panel on Climate Change (IPCC) A1B GHG scenario. Chemical boundary conditions were provided from a global chemistry model linked with the GISS II' GCM (Mickley et al., 1999), and the same isolated climate assumptions were made where anthropogenic emissions were held at current 2000 levels across the globe.

In this approach, it had originally been decided that consistency between the GCM and the global chemistry model was a priority; however, this is one of the "lessons-learned" from the original pilot because this requirement decreased the options available for the regional climate downscaling. GISS II' is a very coarse model having $4^{\circ}\times5^{\circ}$ grids. This very coarse resolution is a likely cause of some evaluation issues identified in the regionally downscaled MM5 results under current climate (Poster 4.1, Gustafson and Leung, 2007). While global chemistry fields driven by other GCMs were not available for this pilot project, the inconsistencies between the global chemistry fields and the GCM would probably have been less important than having better quality regional climate scenarios. In our future directions, this is one of the changes in the approach that we will be adopting. Additionally, the FY-2008 Congressional omnibus funding has allowed us to begin development of new regional downscaled climate scenarios using the Weather Research and Forecasting (WRF) model with several of the most state-of-the-science GCMs including the NASA GISS ModelE and the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1 GCMs. The evaluation of these downscaled scenarios under current climate will be of highest priority, after which the approaches for providing chemical boundary conditions to the regional domain will be considered.

While the impact of regional climate biases on the air quality predictions were a concern, comparison of CMAQ air quality simulations driven by the MM5 regional climate scenarios versus a "standard" MM5 simulation demonstrated that the choice of chemical mechanism had a larger impact on positive ozone (O_3) biases than the regional climate scenarios. Positive temperature and negative precipitation biases in the MM5 regional climate scenario could both contribute to O_3 overpredictions; however, the SAPRC chemical mechanism clearly has the largest influence on O_3 overpredictions regardless of using "standard" MM5 or MM5 regional climate scenarios under current conditions. SAPRC, however, has shown better O_3 response to meteorological variations from cooler, wetter summer to hotter, drier summer conditions than CB4 (Gilliland et al., 2008), which suggests that even with these overprediction biases in SAPRC it is still a better choice of chemical mechanism for studying the O_3 response to future climate change scenarios for this pilot study.

Comparison of CIRAQ's CMAQ air quality simulations under the current and future (ca. 2050) MM5 regional climate scenario suggested that summer average O_3 could increase regionally by approximately 2-5 ppb and highest O_3 levels at the $\geq 95^{th}\%$ could increase by more than 10-15 ppb in the same regions. The modeling results also suggested an extension of the O_3 season into October for much of the nation, which is strongly dependent on the regional climate scenarios having more summer-like conditions during this period under future climate. The results demonstrated that areas that are currently compliant with the O_3 NAAQS could exceed the standard under future climate conditions, and that control strategies assuring compliance with the O_3 NAAQS under current conditions could be inadequate if the impact of future climate is not considered. The locations of simulated O_3 increases under future climate are notably uncertain, and are directly influenced by where large changes are simulated in temperature, cloud and precipitation patterns, and solar radiation reaching the surface. Comparisons with three other modeling studies using similar global to regional modeling approaches (Poster 4.2, Weaver et al., in review) show that AMAD's CIRAQ results have the most conservative O_3 increases under future climate, except for an IPCC B1 scenario that assumes large GHG controls and has very small temperature increases under future climate. The CIRAQ O_3 increases are probably smaller, in part, because of the A1B scenario versus the A2 and A1Fi scenarios in two of the other simulations in Weaver et al. (in review), but also because of our inclusion of boundary conditions from a global model under future climate. Nolte et al. (2008) (Poster 4.1) show O_3 boundary conditions at the western side of the continental U.S. CMAQ domain that are 6 ppb lower than those used in the other studies. These changes in boundary conditions had a larger impact on the (future – current) O_3 change than did isoprene emission changes (Nolte et al., 2008). These impacts from large-scale transport of O_3 under the future scenarios had not been considered in the three other modeling studies included in Weaver et al. (in review), which provides additional reason for the CIRAQ O_3 results being smaller. Adding further to the conservative estimate of O_3 increases in the CIRAQ modeling study, Nolte et al. (2008) demonstrated that if methane levels had been increased in the CMAQ future scenario to be consistent with IPCC A1B methane trends, this would have led to additional increases in maximum daily 8-h average O_3 levels across the U.S. domain of approximately 1-2 ppb on average.

The CIRAQ pilot modeling study has demonstrated that regional climate scenarios and linkages to GCMs are fundamental priority areas for further research on climate and air quality interactions. Regional climate scenarios also provide information about how temperature and precipitation may change under future climate, which are needed in ecosystem and water quality impact assessments. The original CIRAQ study plan was to consider how fine particulate matter ($PM_{2.5}$) scenarios are impacted by the regional climate scenario and by future emission scenarios. While this analysis is underway, results suggest that increased precipitation in the future climate scenario dominate the impact on $PM_{2.5}$. Given that precipitation is one of the most uncertain aspects to meteorological modeling, it has been concluded that it is essential to develop a robust ensemble of regional climate scenarios for further assessment of climate impacts on air quality. Additionally, future emission scenarios can vary wildly depending on assumptions (e.g., IPCC scenario, technology changes). For example, if IPCC A2 and A1B scenario assumptions were applied to NO_x emission reductions for the U.S., CMAQ simulations would result in increased O_3 (A2) or decreased O_3 (A1B) as shown in Hogrefe et al., 2004 versus Nolte et al., 2008. Clearly, a range of emission assumptions is needed to bound the future scenarios of air quality and climate.

Very closely related to the emission scenarios is the potential impact of air quality and air quality trends on climate. The Climate Change Science Program (CCSP) Synthesis and Assessment Product (SAP) 3.2 "Climate Projections based on Emission Scenarios of Long-lived and Short-lived Radiatively Active Gases and Aerosols" demonstrated that the emission trends assumed for black carbon and SO_2 would have a significant impact on the contribution of air pollutants on the climate trend over the next fifty years. Results using global scale climate and chemistry models with direct (and indirect, in one global model) feedbacks from the aerosols and ozone to radiation suggest that air pollutants could contribute approximately 20% to the warming trend out to 2050 even with varying assumptions about the black carbon emission trends (Levy et al., 2008). The SAP 3.2 results demonstrate that air quality management decisions on national scales can have global scale impacts on climate. Having integrated air quality management tools that include climate interactions (both climate impacts on air quality and air quality impacts on climate) would be needed to assess how air quality management decisions are affected by and effect future climate.

As an additional step toward a program that comprehensively includes air quality and climate interactions, the CMAQ model is being extended into the 2-way coupled WRF-CMAQ (Poster 4.3). WRF-CMAQ includes direct feedbacks to the radiation model in WRF at a sub-hourly frequency, so that the scattering and absorbing properties of aerosols and gases are accounted for within the WRF's radiation component. Under conditions of high $PM_{2.5}$ atmospheric loadings, such as during wildfire episodes, these feedbacks are needed to capture the decreased temperatures, photochemistry, and planetary boundary layers associated with heavy loading of scattering aerosols. Similarly, the longer-term impact on the radiation budget with large changes in black carbon, sulfate, or O_3 can be investigated with the integrated WRF-CMAQ model. To capture the climate trend from such changes, comprehensive GCMs will be needed, but it is anticipated that WRF-CMAQ results on continental and hemispheric scales can be used to inform the assumed concentration changes in air pollutants for these studies. As partnerships continue to develop with the global climate modeling community, the exact approach(es) for incorporating air quality trend impacts on future climate will be developed, but the integrated WRF-CMAQ is an important step toward introducing climate and air quality interactions more comprehensively into the program.

9.2 Future Research

With the additional funding from the Congressional FY-2008 omnibus appropriations, new efforts are underway for regional climate downscaling. Linkages of the WRF pre-processor to both the NOAA CM2.1 GCM and the NASA GISS ModelE GCMs are being tested, and this will be followed by rigorous evaluation under current climate conditions. Once the downscaling methods have been fully tested and evaluated, a series of current and future climate downscaling scenarios will be developed based on the CM2.1 and ModelE fields available to us. Additional GCMs may also be included (e.g., NCAR's CCSM) if sub-daily GCM fields are provided to us. Future scenarios such as IPCC A2 and the new Representative Concentration Pathways (RCPs) will be used in these downscaling simulations.

Building on our partnerships with the global modeling community, it is essential that approaches be developed to incorporate national and regional scale air quality trends into future climate projections. Decisions must be made regarding whether EPA will need the ability to generate its own GCM simulations as part of an integrated climate-air quality decision-making tool set, or whether having the integrated WRF-CMAQ's radiative budget impacts would be sufficient for EPA needs. These decisions cannot be fully made until it is clearer that climate mitigation will be mandated through the CAA or new legislation. A future challenge here will also be to determine AMAD's role in the climate community given its air quality and meteorological expertise on a regional scale.

Future emission scenarios is the other area of research that is underway, where emission scenarios are being developed based on the U.S. Senate's Lieberman-Warner-Boxer bill's cap and trade CO_2 controls from utilities and mobile fleet and fuel changes. Sensitivities will be investigated on the criteria pollutant impacts from these emission changes, and instrumented versions of CMAQ (e.g,. CMAQ-DDM, process analysis, etc.) will be used as appropriate to better understand the air quality changes simulated.

9.3 Impact

The AMAD CIRAQ project contributed to the ORD interim national air quality assessment (ORD, 2008; Weaver et al., 2008) and the CCSP SAP 3.2 (Levy et al., 2008). While a relatively small project within the Division, the team developed and influenced the modeling approach used by the NCER grants program on climate and air quality and demonstrated how this approach could be used in air quality management tools.

At this point, many transitions are underway as EPA wrestles with its role in GHG mitigation and climate protection. The CIRAQ pilot project has anticipated the tools and approaches that EPA's Office of Air and Radiation and especially the Office of Air Quality Planning and Standards will need to incorporate climate protection into the current paradigm of air quality management.

9.4 Session Posters

The following three (3) posters will be presented in this session:

(1) On the Linkage of Global and Regional Models to Assess Climate Change – Air Quality Interactions (4.1)
(2) Building a Regional Climate Program: Collaborations and Partnerships (4.2)
(3) Current Research Developments: The Coupled WRF-CMAQ Modeling System (4.3)

Abstracts for each of these posters follow.

On the Linkage of Global and Regional Models to Assess Climate Change–Air Quality Interactions (4.1)

Christopher Nolte, Alice Gilliland, Robert Gilliam, William Benjey, Kristen Foley, Steven Howard, Ellen Cooter

Collaborators: Loretta Mickley and Daniel Jacob (Harvard University), Ruby Leung (Pacific Northwest National Laboratory), Peter Adams and Pavan Racherla (Carnegie Mellon University), Christian Hogrefe (State University of New York at Albany).

Air quality is determined both by emissions of hydrocarbons and oxides of nitrogen and by meteorological conditions, including temperature, wind flow patterns, and the frequency of precipitation and stagnation events. For air quality management applications, regional-scale models are used to assess whether various emission control strategies maintain compliance with the National Ambient Air Quality Standards (NAAQS). These modeling applications typically assume present meteorological conditions, which means that potential changes in climate are not included in the assessment. With emission controls that are implemented over several decades, future climate trends could impact the effectiveness of these controls, which could cause failures to comply with the NAAQS. AMAD initiated the Climate Impact on Regional Air Quality (CIRAQ) project in 2002 to develop a pilot modeling study to incorporate regional-scale climate effects into air quality modeling. It involved collaboration with several academic groups with global-scale modeling expertise, which were supported through the EPA Science To Achieve Results (STAR) grant program. A partnership was also established with the Pacific Northwest National Laboratory (PNNL) to develop regional climate scenarios. Evaluation of the regional climate model (RCM) results identified biases in the RCM's predicted surface temperature under the current climate as compared to "standard" meteorological simulations with data assimilation of meteorological observations. While issues such as temperature biases were identified, precipitation biases were actually lower than in "standard" meteorological predictions, which is notable because precipitation is not included in the data assimilation. Evaluation of the CMAQ air quality predictions showed that meteorological biases were not the dominant influence on O_3 biases; rather, it was the SAPRC chemical mechanism. CMAQ results under the future RCM scenario result in average O_3 increases of approximately 2-5 ppb and 95th percentile (i.e., 4th highest) O_3 increases greater than 10 ppb in some regions. RCM changes in temperature and solar radiation reaching the surface appear to be the largest meteorological factors influencing these modeled increases. Model sensitivity tests show that if the O_3 boundary conditions had not gone down in the global chemistry model under future climate, these O_3 increases would have been even larger. Further, with methane concentrations increased to the levels assumed in the Intergovernmental Panel on Climate Change (IPCC) A1B scenario, the increase in modeled O_3 is larger than the increase caused by higher biogenic emissions of isoprene. Based on the issues raised and predominant sensitivities identified in this pilot study, new efforts are underway to develop a robust series of regional climate simulations with more advanced global climate models (GCMs) and a range of future emission scenarios.

The CIRAQ study contributed directly to the EPA Office of Research and Development report *Assessment of the Impacts of Global Change on Regional U.S. Air Quality*, which was led by the National Center for Environmental Assessment. Additionally, results from CIRAQ were included in the U.S. Climate Change Science Program (CCSP) Synthesis and Assessment Product (SAP) 3.2 *Climate Projections Based on Emissions Scenarios for Long-Lived and Short-Lived Radiatively Active Gases and Aerosols.*

Building a Regional Climate Program: Collaborations and Partnerships (4.2)

Alice Gilliland, Christopher Nolte, Robert Gilliam, William Benjey, Kristen Foley, Steven Howard, Ellen Cooter, Jerold Herwehe, and Tanya Otte

Collaborators: Chris Weaver, Brooke Hemming, and Anne Grambsch (National Center for Environmental Assessment, USEPA/ORD); Darrell Winner (National Center for Environmental Research, USEPA/ORD); Drew Shindell (NASA Goddard Institute for Space Studies); Hiram Levy (NOAA Geophysical Fluid Dynamics Laboratory [GFDL]); North American Regional Climate Change Assessment Program (NARCCAP) Team: Isaac Held and Bruce Wyman (NOAA GFDL), Seth McGinnis (National Center for Atmospheric Research)

Future climate change is broadly recognized by the scientific community as a risk of national and international importance. As climate protection becomes more integral to EPA's mission to protect human health and the environment, modeling tools are needed to assess the effectiveness of programs and the potential climate impacts on health and ecosystems. The Division's Climate Impact on Regional Air Quality (CIRAQ) project provided an opportunity to test the linkages between regional air quality modeling tools and global climate and chemistry models. Through this experience, collaborations have developed with global climate modeling experts. Establishing these partnerships and working across EPA/ORD, other government agencies, and academia is critical to a program that depends on expertise in both climate and air quality modeling. With these partners, efforts continue to develop advanced modeling tools that link global climate trends to regional meteorology and air quality models, and to provide modeling tools for EPA assessment of climate impacts on air quality, human health, water availability, and ecosystem stress. Two key products produced from these collaborations are summarized in this poster: the USEPA ORD report on the impacts of global change on regional U.S. air quality (NCEA, 2007; Weaver et al., in review), and the U.S. Climate Change Science Program (CCSP) Synthesis and Assessment Product 3.2 (Levy et al., 2008).

From our ongoing collaborations with groups outside of AMAD on air quality and global climate linkages, we have learned a number of important lessons that will help guide our further research and interactions on this topic. Our partnerships have demonstrated that careful coordination and linkage between global-scale climate/chemistry models and regional-scale models is required to assess potential climate change impacts on regional air quality. In addition, effective partnerships among global and regional modeling groups can lead to the most efficient use of expertise and resources in studying global-to-regional downscaling issues. Large uncertainties exist in global climate model (GCM) predictions of future climate, and these can lead to significant differences among models. Therefore, regional downscaling for air quality projections can benefit from using GCM projections from several different models.

Current Research Developments: The Coupled WRF-CMAQ Modeling System (4.3)

Rohit Mathur, Jonathan Pleim, David Wong, Tanya Otte,
Robert Gilliam, Jeffrey Young, Shawn Roselle

Collaborators: Francis Binkowski and Aijun Xiu, UNC at Chapel Hill

While the role of long-lived greenhouse gases in modulating the Earth's radiative budget has long been recognized, it is now widely acknowledged that the increased tropospheric loading of aerosols can also affect climate in multiple ways. Aerosols can provide a cooling effect by enhancing reflection of solar radiation, both directly (by scattering light in clear air) and indirectly (by increasing the reflectivity of clouds). On the other hand, organic aerosols and soot absorb radiation, thus warming the atmosphere. Current estimates of aerosol radiative forcing are quite uncertain. The major sources of this uncertainty are related to the characterization of atmospheric loading of aerosols, the chemical composition and source attribution of which are highly variable both spatially and temporally. Unlike greenhouse gases, the aerosol radiative forcing is spatially heterogeneous and estimated to play a significant role in regional climate trends. The accurate regional characterization of the aerosol composition and size distribution is critical for estimating their optical and radiative properties and thus for quantifying their impacts on radiation budgets of the Earth-atmosphere system.

Traditionally, atmospheric chemistry-transport and meteorology models have been applied in an off-line paradigm, in which archived output describing the atmosphere's dynamical state as simulated by the meteorology model is used to drive the transport and chemistry calculations of the atmospheric chemistry-transport model. A modeling framework that facilitates coupled on-line calculations is desirable because it (1) provides consistent treatment of dynamical processes and reduces redundant calculations, (2) provides the ability to couple dynamical and chemical calculations at finer time steps and thus facilitates consistent use of data, (3) reduces the disk-storage requirements typically associated with off-line applications, and (4) provides opportunities to represent and assess the potentially important radiative effects of pollutant loading on simulated dynamical features. To address the needs of emerging assessments for air quality-climate interactions and for finer-scale air quality applications, AMAD recently began developing a coupled atmospheric dynamics-chemistry model: the two-way coupled WRF-CMAQ modeling system. In the prototype of this system, careful consideration has been given to its structural attributes, to ensure that it can evolve to address the increasingly complex problems facing the Agency. The system design is flexible regarding the frequency of data communication between the two models, and can accommodate both coupled and uncoupled modeling paradigms. This approach also mitigates the need to maintain separate versions of the models for on-line and off-line modeling.

In the prototype coupled WRF-CMAQ system, the simulated aerosol composition and size distribution are used to estimate the optical properties of aerosols, which are then used in the WRF radiation calculations. Thus, the direct radiative effects of absorbing and scattering tropospheric aerosols estimated from the spatially and temporally varying simulated aerosol distribution can be fed back to the WRF radiation calculations; this results in a "two-way" coupling between the atmospheric dynamical and chemical modeling components. This extended capability provides unique opportunities to systematically investigate how atmospheric loading of radiatively important trace species affects the Earth's radiation budget. Consequently, this modeling system is expected to play a critical role in the Agency's evolving research and regulatory applications exploring air quality-climate interactions.

9.5 Session Publications

This section presents the products (generally from 2004-2008) associated with each poster in this session. Some products are associated with multiple posters, so they are listed as products under more than one poster.

On the Linkage of Global and Regional Models to Assess Climate Change–Air Quality Interactions (4.1)

Cooter, E.J., **R. Gilliam**, **W. Benjey**, **C. Nolte**, **J. Swall**, and **A. Gilliland** (2007), Examining the impact of changing climate on regional air quality over the U.S. Air Pollution Modeling and its Application XVIII, C. Borrego and E. Renner, eds., Elsevier, 633-647.

Jacob, D. and **A.B. Gilliland** (2005), Modeling the impact of air pollution on global climate change, EM, October 2005, 24-26.

National Center for Environmental Assessment, Assessment of the Impacts of Global Change on Regional U.S. Air Quality (External Review Draft, 2007), U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-07/094.

Nolte, C.G., **A.B. Gilliland**, C. Hogrefe, and L.J. Mickley (2008), Linking global to regional models to assess future climate impacts on surface ozone levels in the United States. J. Geophys. Res., 113, D14307.

Nolte, **C.**, **A. Gilliland**, and C. Hogrefe (2008), Linking global and regional models to simulate U.S. air quality in the year 2050. Air Pollution Modeling and its Application XIX, C. Borrego and A. I. Miranda, eds., Elsevier, 559-567.

U.S. Climate Change Science Program (2008), Climate Projections Based on Emissions Scenarios for Long-Lived and Short-Lived Radiatively Active Gases and Aerosols, H. Levy II, D. Shindell, **A. Gilliland**, L.W. Horowitz, and M. D. Schwarzkopf, eds., U.S. Department of Commerce, National Climatic Data Center, Washington, DC..

Weaver, C.P., X.-Z. Liang, …, **C. Nolte**, …, **A. Gilliland**,… (2008). A preliminary synthesis of modeled climate change impacts on U.S. regional ozone concentrations. Bull. Amer. Meteor. Soc., in review.

Building a Regional Climate Program: Collaborations and Partnerships (4.2)

National Center for Environmental Assessment, Assessment of the Impacts of Global Change on Regional U.S. Air Quality (External Review Draft, 2007), U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-07/094.

U.S. Climate Change Science Program (2008), Climate Projections Based on Emissions Scenarios for Long-Lived and Short-Lived Radiatively Active Gases and Aerosols, H. Levy II, D. Shindell, **A. Gilliland**, L.W. Horowitz, and M. D. Schwarzkopf, eds., U.S. Department of Commerce, National Climatic Data Center, Washington, DC.

Weaver, C.P., X.-Z. Liang, …, **C. Nolte**, …, **A. Gilliland**, … A preliminary synthesis of modeled climate change impacts on U.S. regional ozone concentrations. Bull. Amer. Meteor. Soc., in review.

Current Research Developments: The Coupled WRF-CMAQ Modeling System (4.3)

Byun, D.W. and **K.L. Schere** (2006), Review of governing equations, computational algorithms, and other components of the Models-3 Community Multiscale Air Quality (CMAQ) modeling system, *Applied Mechanics Review*, 59, 51-77

Pleim, J., J. Young, D. Wong, R. Gilliam, T. Otte, and **R. Mathur** (2008), Two-Way Coupled Meteorology and Air Quality Modeling, *Air Pollution Modeling and Its Application XIX*, C. Borrego and A.I. Miranda (Eds.), 496-504, ISBN 978-1-4020-8452-2, Springer, The Netherlands.

Prototype version of the 2-way coupled WRF-CMAQ modeling system (2008) represented the successful completion of an EPA Annual Performance Measure (APM). A public release of the complete modeling system is scheduled for 2011