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Interactions of Climate Change and Air Quality: Research Priorities and New Direction

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INTERACTIONS OF CLIMATE CHANGE AND AIR QUALITY: RESEARCH PRIORITIES AND NEW DIRECTIONS

Report from a Workshop held by the Electric Power Research Institute (EPRI)
April 26-27, 2005
Washington, DC

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ABSTRACT

Regional air quality and global climate change are highly interrelated because emissions of many pollutants affect both air quality and climate change, and the fundamental chemistry affecting air quality and global climate is similar. There are major gaps in scientific understanding that limit the development of models that can be used to accurately assess impacts of the interactions between air quality and climate on global to regional scales. A two-day workshop was held to identify such gaps and develop a research agenda for the scientific community. The workshop was attended by eminent scientists in both the air quality and the global climate fields and by the program managers at various federal research agencies (DOE, EPA, NASA, NOAA, NSF). The first session consisted of presentations by federal research agencies describing their involvement and interests in this area. This was followed by a series of research presentations. The final afternoon was devoted to development and synthesis of recommendations. This report describes the specific research recommendations that were developed as part of the workshop.

INTRODUCTION

Better understanding of the interactions between climate change and regional air quality is an emerging priority for research and policy. Developed countries such as the United States are aggressively pursuing improvements in air quality through emission controls targeted at reducing particulate matter and ozone. However, these pollutants also affect climate in important and complicated ways. Climate change, in turn, could have large impacts on regional air quality. The effects of climate change on the environmental cycles of contaminants such as mercury and persistent organic pollutants (POPs) are also of concern. Consequently, it is important to assess the climate impacts of policies directed at air quality and vice versa. Such assessments must be based on accurate physical models that account for the interactions between atmospheric components and climate on global to regional scales. Presently, there are major gaps in scientific understanding that limit the development of such models. The purpose of this report is to identify the gaps where focused research programs would earn large dividends.

Aerosol particles and tropospheric ozone are pollutants of worldwide concern that are also known to make significant contributions to radiative forcing of climate. Their lifetimes are short (days to weeks) so that their concentrations respond rapidly to changes in emissions, offering a potentially powerful lever to affect near-term climate change. Ozone, a major greenhouse gas, and light-absorbing aerosols such as black carbon (BC) have a global warming effect. Other aerosols such as sulfate scatter solar radiation and have a cooling effect. Aerosols also produce an indirect effect on climate by serving as cloud condensation nuclei (CCN) and modifying the radiative and precipitation properties of clouds. The mechanisms and implications of this indirect effect are extremely complex and poorly understood. Aerosol direct and indirect effects can also yield large impacts on regional hydrological cycles.

Climate variability and change will affect air quality through perturbations to winds, atmospheric mixing depths, frequencies of stagnation events, temperature, precipitation and other meteorological variables. Little research has been done to date to study the impacts of climate change on air pollution meteorology. Climate change will also affect emissions associated with fires, dust storms, lightning, aquatic systems, soils, and vegetation. Perturbations to the atmospheric deposition and ecosystem cycling of bio-accumulating pollutants, such as mercury and POPs, add to the complexity of assessing the environmental impact of climate change.

Linking research efforts directed at air quality and climate change could result in mitigation approaches for both air quality and climate change that are overall more cost-effective. In order to identify the critical research priorities, the Electric Power Research Institute (EPRI) convened a workshop of eminent U.S. scientists with a broad range of expertise. The workshop was organized by EPRI program manager Naresh Kumar and took place on April 26-27, 2005 at the EPRI offices in Washington, DC. This report presents the recommendations from the workshop.

WORKSHOP CHARGE AND ORGANIZATION

The charge to the workshop was to develop a research agenda targeted at the following two questions:

- What are the effects of air pollutants on climate change?
- What are the effects of climate change on air quality?

The first question focused on aerosols, tropospheric ozone, and related anthropogenic species as agents for climate change on both global and regional scales. The second question encompassed the effects of climate change on tropospheric ozone, aerosols and mercury.

The workshop agenda is provided in Appendix A. The first session consisted of presentations by federal research agencies (DOE, EPA, NASA, NOAA, NSF) describing their involvement and interests in this area. This was followed by a series of research presentations. One-paragraph summaries of these presentations are given in Appendix B. The final afternoon was devoted to development and synthesis of recommendations.

RECOMMENDATIONS

The ultimate goal of research directed at interactions of climate change and air quality is:

> *The construction of global models that can describe the effects of air pollutants on climate, the effects of climate change on air quality, and the interactions of these effects in a manner that can guide the development of scientifically sound policy.*

Constructing such models is a formidable problem that requires major progress in our underlying knowledge of physical, chemical and biological processes. Advances in this knowledge will require a combination of theoretical research, laboratory studies, field observational programs, and related analyses that can inform, test, constrain, and improve the models.

The workshop found it useful to categorize its recommendations for future research into seven themes:

1. Aerosol model simulation capabilities
2. Aerosol forcing estimates
3. Specific issues relating to black carbon aerosol
4. Tropospheric ozone and related chemistry
5. Effects of climate change on air quality
6. Effects of climate change on mercury
7. Systems models

Specific recommendations for each theme are listed below, and Section 4 provides further elaboration. The recommendations are listed in order from the most general to the most specific, with no attempt to prioritize. However, within each theme, we identify two new research directions that presently are receiving insufficient attention and where research investments are needed in particular.

RECOMMENDATIONS FOR FUTURE RESEARCH

1. Aerosol model simulation capabilities

1.1 Improve simulations of aerosol mixing states, size distributions, and CCN activities.

1.2 Better characterize aerosol sources through a combination of process and inverse models.

1.3 Better understand the processing of aerosols from large concentrated sources such as fires and megacities.

1.4 **New direction**: Test global models against observed vertical profiles of aerosols.

1.5 **New direction:** Mine air quality data from monitoring networks in North America and Europe to determine long-term aerosol trends and assess the ability of models to reproduce them.

2. Aerosol forcing estimates

2.1 Better understand the coupling of aerosols to the hydrologic cycle.

2.2 Improve characterization of aerosol optical properties in relation to composition.

2.3 Assimilate aerosol observations into climate models to seek evidence of regional climate forcing.

2.4 **New direction**: Explain the observed long-term trends of solar radiation at the surface in North America.

2.5 **New direction**: Understand aerosol effects on climate variability and extremes.

3. Specific issues relating to black carbon aerosol

3.1 Improve emission inventories and scavenging parameterizations in global models.

3.2 Improve understanding of BC-cloud interactions.

3.3 **New direction**: Better understand the effects of the vertical distribution of BC on atmospheric heating rates and the implications for climate.

3.4 **New direction**: Measure the effects of BC on the albedo of important snow and ice fields including sea ice, mountain glaciers, and Greenland.

4. Tropospheric ozone and related chemistry

4.1 **New direction**: Improve the ability of global models to reproduce observed long-term trends in background tropospheric ozone.

4.2 Improve understanding of methane source processes and their geographical distribution.

4.3 **New direction**: Better understand the factors controlling the concentrations and trends of tropospheric hydroxyl (OH) radicals, and the implications for the methane lifetime.

4.4 Better understand the role of heterogeneous oxidant chemistry on ozone and aerosol budgets.

4.5 Better understand the sensitivity of stratosphere-troposphere exchange to climate change.

5. Effects of climate change on air quality

5.1 **New direction**: Produce ensemble general circulation model (GCM)/regional climate model (RCM) simulations to analyze the effects of climate change on air pollution meteorology and regional air quality.

5.2 **New direction**: Construct two-way linkages between regional air quality models and RCMs.

5.3 Better quantify biogenic emissions of volatile organic compounds (VOC) and their dependences on meteorological and atmospheric composition variables.

5.4 Better understand the relationship of wildfires to climate variables.

5.5 Better understand how climate-driven changes in land cover may affect air quality.

6. Effects of climate change on mercury cycling

6.1 **New direction**: Better understand the atmospheric chemistry of mercury and the effect of a changing climate on the patterns of mercury deposition.

6.2 **New direction**: Examine the effects of climate change on mercury cycling in aquatic ecosystems, especially marine, and including re-emission to the atmosphere.

6.3 Better understand the role of biomass fires as sources of mercury.

7. System models integrating climate change, air quality, economics, and policy

7.1 Achieve better coupling between system model components (submodels) including development of knowledge at the interfaces.

7.2 Assess the joint impacts of different energy policies on air quality and climate change.

7.3 **New direction**: Explore scenarios for improving air quality without incurring a major climate penalty.

7.4 **New direction**: Improve computational efficiency of physical, chemical, and biological submodels.

DISCUSSION OF RECOMMENDATIONS

1. Aerosol model simulation capabilities

Models are presently very limited in their capabilities to simulate aerosol concentrations as is needed for simulations of climate forcing. A number of priority tasks must be addressed.

1.1. **Improve simulations of aerosol mixing states, size distributions, and CCN activities.** The optical properties and CCN activities of aerosol particles are determined by their chemical composition and size, but global models are very primitive in their ability to simulate these. This is partly a computational problem, as resolving the continuum of size distribution and composition quickly makes aerosol simulations intractable. Development of computationally efficient algorithms that capture the essential processes determining aerosol optical properties and aerosol-cloud interactions is essential. It is also important to obtain more observations of size-resolved aerosol composition, particularly above the boundary layer where few measurements are available.

1.2. **Better characterize aerosol sources through a combination of process and inverse models.** Current understanding of aerosol sources including in particular dust and organic matter is severely lacking. Research is needed at the process level, using laboratory and field studies, and at the top-down level, using inverse models to interpret atmospheric observations including those from satellite platforms. A strong synergy between inverse and process model studies is needed in which results from the former are used to improve the latter.

1.3. **Better understand the processing of aerosols from large concentrated sources such as fires and megacities.** Fires are major global sources of carbonaceous aerosols and are expected to increase in frequency over the next decades, at least at boreal latitudes, due to climate warming and the legacy of fire suppression practices. Megacities are major global sources of anthropogenic aerosols, particularly in the developing world. There is a strong need to better understand the evolution of aerosols (chemistry, mixing state, size distribution) in these concentrated plumes as they disperse into the global atmosphere over spatial scales of hundreds of kilometers.

1.4. **New direction: Test global models against observed vertical profiles of aerosols.** The atmospheric column and vertical distribution of aerosols are of central importance for characterization of climate forcing, but observations of aerosols so far have been largely limited to surface air. Such observations are usually not representative of the broader troposphere. Vertical profile information on aerosols from aircraft missions, long-term light detection and ranging instruments (lidars), and space-based lidars are becoming increasingly available, but have so far received insufficient use for testing global models. Preliminary results suggest that models have large difficulties in reproducing the vertical structure of plumes vented from source regions, as well as the abundance and chemical composition of aerosols in the upper troposphere.

1.5. **New direction: Mine air quality data from monitoring networks in North America and Europe to determine long-term aerosol trends and assess the ability of models to reproduce them.** The global models used to compute aerosol forcing of climate have not been adequately tested against long-term aerosol observations. Overlooked by the research community are large records of aerosol concentration and deposition data collected routinely in North America and Europe (and increasingly in East Asia) to

serve air quality monitoring needs. Some of these networks span several decades, and they generally include background sites that would be of particular value for testing global models. There is a compelling need to compile and evaluate these data in a way that will make them easily accessible by the global modeling community.

2. Improving aerosol forcing estimates

Quantifying aerosol forcing of climate in global models involves characterization of aerosol optical properties, coupling to the hydrologic cycle, and analysis of radiative forcing observations. Several major gaps need to be addressed.

2.1. **Better understand the coupling of aerosols to the hydrologic cycle.** Simulation of relative humidity (RH), clouds, and precipitation – i.e., the atmospheric component of the hydrological cycle – is notoriously difficult for both global and regional models. Calculating the indirect effect of aerosols complicates the problem with the need to properly account for local aerosol-cloud interactions, updraft velocities (which affect CCN activation), the scavenging of aerosols by precipitation, and the behavior of aerosol particles in the high-humidity environments around clouds. Work is needed to improve understanding of the coupled evolutions of aerosol and cloud droplet size distributions in clouds, and the implications for precipitation formation and aerosol scavenging. This work must involve development of cloud-resolving models for describing the microphysical processes, and increasing computational efficiency (parameterizations) of these models for application in global models. New observations for constraining and testing these model representations are rapidly becoming available from aircraft missions (e.g., the DOE aircraft program) and from satellites (e.g., the NASA A-train).

2.2. **Improve characterization of aerosol optical properties in relation to composition.** Simulation of the radiative forcing by aerosols requires information on the RH-dependent optical properties as a function of atmospheric composition. This is a complicated problem because aerosol particles are complex mixtures of many different chemical species, and often include more than one phase. Given our current understanding and the computational requirements, current models cannot capture this complexity, and must resort to lumping of species and simple assumptions regarding mixing state. How to achieve a realistic description of aerosol optical properties based on a limited set of aerosol model variables is a major challenge that needs to be addressed through process modeling, field observations, and laboratory studies.

2.3. **Assimilate aerosol observations into climate models to seek evidence of regional climate forcing.** Aerosols should have detectable regional effects on temperatures and precipitation in major source regions. These effects need to be identified, both for their intrinsic interest and as a means for testing models. One approach that deserves further exploration is the assimilation in GCMs of aerosol observations (in particular optical depth observations from space) together with the usual suite of meteorological variables. The assimilation process could help to determine whether GCM-simulated aerosol effects on regional climate are consistent with observations.

2.4. **New direction: Explain the observed long-term trends of solar radiation at the surface in North America.** Observations at many sites throughout the world have registered changes of several percent in solar radiation at the surface over the past decades. This effect is puzzling and needs to be better understood. The implied

surface radiative forcing is very large and would seem to require major cloud effects that may or may not be driven by aerosol indirect effects. A focus on North American sites could illuminate this issue by leveraging on concurrent long-term trends available for aerosols and clouds.

2.5. **New direction: Understand aerosol effects on climate variability and extremes.** Model studies of aerosol forcing of climate have focused so far on the implications for mean regional temperatures, cloudiness, and precipitation. There is a need to better understand the consequences of aerosol forcing on large-scale climate variability, including the major climate modes (e.g., El Nino Southern Oscillation, Arctic Oscillation), as well as extreme weather.

3. Specific issues relating to black carbon aerosol

Aerosol components that absorb solar radiation, primarily black carbon (BC), play a unique role in climate modification. They heat the atmosphere, thus modifying atmospheric stability with complicated consequences on regional climate. They can greatly modify the optical properties of clouds, and the albedo properties of snow. We consider in this section several research issues unique to black carbon.

3.1. **Improve emission inventories and scavenging parameterizations in global models.** Global models implementing current best estimates of BC emissions often incur large biases when compared to observed BC atmospheric concentrations. BC emissions are difficult to quantify as they involve a variety of small sources of inefficient combustion. There is a need to improve emission inventories. It is also important to better characterize the scavenging efficiency of BC, including both in-cloud and below-cloud processes, and its dependence on chemical aging of BC in the atmosphere.

3.2. **Improve understanding of BC-cloud interactions.** More work is needed to understand the cloud activation properties of BC and other light-absorbing particles, and the subsequent effects on cloud optical properties and cloud evolution. Absorbing CCN may decrease cloud albedo considerably, with the droplet acting as a focusing agent to increase the magnitude of light absorption. Local heating from the light absorption could in turn lead to cloud evaporation and hence suppression of precipitation. Field observations and improved microphysical process models are needed to test and improve the parameterizations used in global models.

3.3. **New direction: Better understand the effects of the vertical distribution of BC on atmospheric heating rates and the implications for climate.** BC aerosols vented to the free troposphere affect the local stability of the atmosphere through local heating, with complex climate consequences. Cloud updraft velocities and the large-scale circulation may also be affected by this BC heating. There is still little information, either from models or from observations, on what those consequences may be. Field measurements of concurrent vertical profiles of BC concentrations, radiation fluxes, and heating rates, together with regional model simulations would begin to fill this gap.

3.4. **New direction: Measure the effects of BC on the albedo of important snow and ice fields including sea ice, mountain glaciers, and Greenland.** Quantifying the climate forcing from deposition of BC on snow and ice is largely limited by lack of data on the albedo effect per unit of deposited BC. Better knowledge requires direct

measurements of albedo together with BC content for snow and ice fields of different morphologies. The measurements need to be highly accurate, as albedo perturbations as small as 0.1% could have important impacts.

4. Tropospheric ozone and related chemistry

Tropospheric ozone is a major greenhouse gas, but there is large uncertainty in the magnitude of its global radiative forcing since preindustrial times (0.2-0.8 W m^{-2}). The precursor gases to tropospheric ozone formation—nitrogen oxides (NOx) volatile organic compounds (VOC), and carbon monoxide (CO) —through related chemistry influence hydroxyl (OH) radical concentrations (key atmospheric oxidants) and hence the lifetime of methane, another major greenhouse gas. In turn, methane is a major precursor for background tropospheric ozone. Methane has shown variable trends over the past decades that are poorly understood and could provide important information on its sources.

4.1. **New direction: Improve the ability of global models to reproduce observed long-term trends in background tropospheric ozone.** Current models have difficulty reproducing the observed trends in background tropospheric ozone over the 20th century and over the past few decades. This difficulty raises questions as to our understanding of the natural sources of ozone precursors and their possible perturbation by human activity. Lightning NOx is thought to be the dominant natural precursor of ozone on a global scale but source estimates are uncertain by an order of magnitude. The effect of climate change and aerosol pollution on lightning activity has received little attention so far. Biomass fires are also a large global source of NOx, but our understanding of the magnitude of this source, plume heights, and plume chemistry is inadequate. Major advances on this problem should be possible by exploiting new satellite observations of tropospheric composition and underlying processes (e.g., lightning and fires) to test and improve global ozone models.

4.2. **Improve understanding of methane source processes and their geographical distribution.** Methane concentrations rose by 1-2% yr^{-1} in the 1970s and 1980s. Since then the mean rate of growth has decreased to less than 0.5% yr^{-1}, with indication that concentrations may be stabilizing, though with considerable year-to-year variability. Future-climate projections assume an increase in methane over at least the first half of the 21st century, but the recent data suggest that future increases could be curbed or reversed. Better understanding of the observed methane trends in relation to sources is necessary. Inverse model analyses need to be pursued using observations from surface networks as well as from aircraft and satellite missions.

4.3. **New direction: Better understand the factors controlling the concentrations and trends of tropospheric OH, and the implications for the methane lifetime.** Direct measurements of OH over the past decade have demonstrated a good first-order understanding of the processes controlling OH concentrations locally. At the same time, long-term measurements of halocarbon concentrations (in particular methylchloroform) have provided strong constraints on global OH concentrations and have enabled estimates of OH trends. The halocarbon data suggest large trends in OH over the past three decades, increasing in the 1980s, decreasing in the 1990s, and then increasing again. These trends have major implications for the lifetime of methane and hence for methane trends, but they have yet to be explained by global models of tropospheric chemistry.

4.4. **Better understand the role of heterogeneous oxidant chemistry.** Global model simulations of tropospheric ozone, OH, and aerosol particle formation are highly sensitive to heterogeneous chemistry involving aerosols. Reactions of ozone and NOx on dust, sea salt, and organic particles are potentially important but poorly characterized. Laboratory studies to determine mechanisms and rate constants are needed.

4.5. **Better understand the sensitivity of stratosphere-troposphere exchange to climate change.** Although stratosphere-troposphere exchange (STE) is only a minor source of tropospheric ozone on a global scale, it could be important in the upper troposphere where ozone has a large greenhouse effect. STE is expected to be highly sensitive to climate change through perturbations to the general circulation of the stratosphere, but this has received little study so far.

5. Effects of climate change on air quality

Climate change could have a large impact on air quality in ways that need to be better understood. Changes in temperature and cloud cover affect the chemistry of ozone and aerosol formation. Changes in air pollution meteorology affect the ventilation of source regions. Natural sources contributing to pollution—including vegetation, fires, and dust—could also be highly sensitive to climate change. These effects need to be addressed in GCMs coupled with regional climate models (RCMs).

5.1. **New direction: Conduct ensemble GCM/RCM simulations to analyze the effects of climate change on air pollution meteorology and air quality.** GCM studies of 21st century climate have so far paid little attention to the implications of climate change on variables important for regional air pollution meteorology (e.g., mixing depths, stability, stagnation events). Evaluating GCM simulations of these variables for the present-day atmosphere is important to develop confidence in prediction skills for future atmospheres. Coupling GCMs to RCMs may be necessary to provide adequate resolution. Projections of changes in air pollution meteorology over the 21st century will require an ensemble of GCM/RCM simulations, using a variety of models, to assess the uncertainty as diagnosed by intermodel variability. Including ozone and aerosol chemistry in these simulations will offer a comprehensive assessment of climate change impacts on air quality. Statistical analyses of observed relationships of ozone and aerosol concentrations with regional-scale meteorological variables are also needed, both for empirical diagnostic of the sensitivity to climate change and for testing the GCM/RCM simulations.

5.2. **New direction: Construct two-way linkages between air quality models and RCMs.** Several efforts are underway in GCMs to include the effects of aerosols on climate, but less attention has been paid to including aerosol effects in the mesoscale meteorological models used to drive regional air quality simulations. The local surface forcing by aerosols can easily be as large as 10-20 Wm^{-2} over source regions, and inclusion of this forcing in RCMs could have a significant impact on the calculations of mixing depths, precipitation, and other meteorological variables. Two-way linkages between aerosol and RCMs would enable the exploration of feedbacks between air pollution and climate on the regional scale, for example due to changes in precipitation scavenging.

5.3. **Better quantify emissions of biogenic VOC and their dependence on meteorological and atmospheric composition variables.** Emissions of isoprene, a major precursor of

tropospheric ozone, are known to be highly sensitive to meteorological variables (e.g., temperature, solar radiation, moisture). Recent research also suggests significant dependence of isoprene emission on ambient carbon dioxide (CO_2) levels. Besides isoprene there are a large number of biogenic VOC (e.g., terpenes, sesquiterpenes, carbonyls, fatty acids) known to be important for organic aerosol formation and also possibly for ozone chemistry. The sensitivity of emissions of these compounds to changes in meteorological variables and atmospheric composition is still poorly understood.

5.4. **Better understand the relationships of wildfires to climate variables.** There has been a large increase in Canadian forest fires since the 1960s that may be at least partly driven by climate change. Acceleration of climate change over the coming decades could have major consequences for fire activity, both at northern mid-latitudes and in the tropics. This issue needs to be better understood at the process level, in terms of the relationships of fires to meteorological variables (precipitation, convection and lightning, extreme events) and to ecosystem variables subject to climate change (vegetation types and biomass loadings). Knowledge of these relationships then must be implemented in GCMs/RCMs to assess the impacts of fires on global atmospheric composition and regional air quality. Rapid improvements in fire data bases from both traditional sources and satellite measurements will help validate model simulations of the interannual variability of fires.

5.5. **Better understand how climate-driven changes in land cover may affect air quality.** Land cover has important implications for air quality through its effects on biogenic emissions, soil hydrology, and albedo. Changes in land cover are at present mainly driven by direct human practices, but climate change and increasing CO_2 may become major drivers by the mid-21st century. There is a need to evaluate the consequences for long-term air quality strategies. Exploration of this issue should be done using GCMs coupled to dynamic vegetation models.

6. Effects of climate change on mercury cycling

Global cycling of mercury (Hg) involves emissions from anthropogenic and natural sources, atmospheric deposition, bio-accumulation and transport in surface reservoirs, and re-emission to the atmosphere. Climate change could have major effects on these processes, thereby altering the fluxes and the production and bioaccumulation of methylmercury (MeHg) in aquatic ecosystems. Atmospheric input of mercury to ecosystems is through deposition of ionic mercury (i.e., Hg^{2+}) produced in the atmosphere by oxidation of elemental mercury. Changes in atmospheric chemistry could thus be important for the future patterns of mercury accumulation in ecosystems.

6.1. **New direction: Better understand the atmospheric chemistry of mercury and the effect of a changing climate on the patterns of mercury deposition.** The reduction-oxidation (redox) chemistry of atmospheric mercury is poorly understood, yet is critical for describing the atmospheric distribution of reactive gaseous mercury (RGM) and particulate mercury, and the resulting mercury fluxes to ecosystems. Measurements of the reaction processes including temperature dependences must be made in the laboratory. The database of atmospheric mercury observations is increasing rapidly, and the potential of inverse models for constraining the sources and chemistry of atmospheric mercury should be explored. GCMs should be applied to simulations of atmospheric mercury for future vs. present-day atmospheres to assess

how changes in atmospheric circulation and precipitation patterns could affect mercury deposition fluxes.

6.2. **New direction: Examine the effects of climate change on mercury cycling in aquatic ecosystems, especially marine, including re-emission to the atmosphere.** Cycling of mercury in terrestrial and marine ecosystems involves processes of atmospheric deposition, biologically mediated methylation/demethylation, transport, and re-emission. All of these processes are highly sensitive to climate change with implications for the global transport and bio-accumulation of mercury. They need to be better understood through development of mercury-specific processes in ecosystem models, and such models need to be coupled to global atmospheric models to assess the impacts of climate change.

6.3. **Better understand the role of biomass fires as sources of mercury.** Biomass fires are significant sources of mercury that could evolve in the future as mercury accumulates in the biosphere. Field measurements are needed to better quantify this source, the associated chemical partitioning of mercury, and the relationship to the mercury content of the burned vegetation.

7. System models integrating climate change, air quality, economics, and policy.

Assessing the economic and societal impacts of policy decisions related to climate change and air quality requires system models that integrate all relevant processes in a credible mechanistic way. Such models have been developed aggressively over the past decade. They require large simulation ensembles to characterize errors and obtain probability distribution functions (pdfs) of the relevant outcomes. Generating these large ensembles poses tremendous computational challenges. Other challenges relate to the proper description of processes at the interface between different model components, i.e. at the boundaries between different research foci.

7.1. **Achieve better coupling between system model components (submodels) including development of knowledge at the interfaces.** The traditional approach to build a system model is to start with state-of-science representations of the different components describing the system (e.g., physical climate, atmospheric chemistry, ecosystem dynamics, economics), simplify these components as necessary for computational tractability, and then integrate them in a systems framework. Presently, the principal weakness of this approach lies at the interface between components, which is interdisciplinary and has received less attention in general.

7.2. **Assess the joint impacts of different energy policies on air quality and climate change.** There is a need to develop energy policy options that consider impacts on both air quality and climate change variables, and the associated economic costs. This will require further development of appropriate system models.

7.3. **New direction: Explore scenarios for improving air quality without incurring a major climate penalty.** There are compelling reasons to improve air quality in major population centers of the world. However, most aerosols exert a negative climate forcing, and decreases in their concentrations could exacerbate warming. Reductions in tropospheric ozone, particularly through methane emission controls, would have a beneficial effect by reducing the positive forcing. There is a need to explore emission control scenarios in which the warming effect of decreasing aerosols can be

compensated through concomitant decreases in greenhouse gases and black carbon aerosol. This can be done by applying system models with a range of possible emission mixes and sources to determine the net air quality, climate, and economic outcomes of different emission reduction strategies.

7.4. **New direction: Improve the computational efficiency of physical, chemical, and biological submodels.** System models typically require hundreds or thousands of simulation years in order to map the pdf space relating policy decisions to physical and economic outcomes. This is one or more orders of magnitude beyond the typical applications of global three-dimensional chemical and aerosol models, and may thus require order-of-magnitude improvements in the computational efficiency of the corresponding modules.

APPENDIX A: WORKSHOP AGENDA

EPRI Workshop on Interactions of Climate Change and Regional Air Quality

Global Climate Change & Air Quality Programs

April 26-27, 2005
EPRI, 2000 L Street, N.W., Suite 805
Washington, DC

Tuesday, April 26

8:00 AM *Continental Breakfast*

8:30 **Welcome and Introductions**
Naresh Kumar • EPRI

8:40 **Agenda and Meeting Objectives**
Daniel Jacob • Harvard University

8:50 **DOE Research Program**
Peter Lunn • DOE

9:10 **EPA Research Program**
Darrell Winner • EPA

9:30 **NASA Research Program**
Phil DeCola • NASA

9:50 **NOAA Research Program**
A. Ravishankara • NOAA, Aeronomy Laboratory

10:10 **NSF Research Program**
Jay Fein • NSF

10:30 *Break*

10:45 **Effects of Air Pollutants on Regional and Global Climate**
Jim Hansen • NASA

11:20 **Coupling of Atmospheric Chemistry, Aerosols, and Climate**
Jeff Kiehl • NCAR

11:55 PM **Discussion**

12:15 *Lunch*

1:15 **Climate Forcings from Anthropogenic and Biomass Burning Aerosols**
Joyce Penner • University of Michigan

1:50 **Black Carbon Effects on Climate**
V. Ramanathan • UC San Diego

2:25 **Aerosol Radiative Forcing**
Steve Schwartz • Brookhaven National Laboratory

3:00 **Discussion**

3:30 *Break*

3:45 **Aerosols: Linking Air Quality and Climate Change**
John Seinfeld • Caltech

4:20 **Tropospheric Ozone: Linking Air Quality and Climate Change**
Daniel Jacob • Harvard University

4:55 **Discussion**

5:15 *Adjourn*

5:30-7:00 *Reception*

Wednesday, April 27

8:15 AM *Continental Breakfast*

8:45 **Effects of Climate Change on Fires**
Jennifer Logan • Harvard University

9:15 **Effects of Climate Change on Air Quality**
S.T. Rao • NOAA / EPA

9:45 **Effects of Climate Change on Mercury Cycling**
Bill Fitzgerald • University of Connecticut

10:15 **Discussion**

10:45 *Break*

11:00 **Integration of Scientific and Policy Issues for Climate Change and Air Quality**
Ron Prinn • MIT

11:45 **Discussion**

12:00 PM *Lunch*

1:00 **Discussion: Synthesis and Recommendations**

4:00 *Adjourn*

APPENDIX B: RESEARCH PRESENTATION SUMMARIES

JAMES HANSEN (National Aeronautics and Space Administration/Goddard Institute for Space Studies) pointed out that the Earth's global mean temperature, due to global warming in the past century, has reached a level at approximately the peak of the current interglacial period and an additional global warming of about one-half degree Celsius in 'in-the-pipeline' due to existing increases of greenhouse gases. All of the IPCC scenarios for the next 50 years have a substantial net increase in climate forcings by non-CO_2 forcings as well as by CO_2. As a result, it will be practically impossible to slow the growth of CO_2 enough to avoid 'dangerous anthropogenic interference' with climate unless there are also aggressive attempts to halt and even reverse the growth of the non-CO_2 forcings, a strategy that would have the benefit of quick improvements in climate forcings, human health, agricultural productivity, and other gains from decreased air pollution. The most effective actions would be those reducing ozone precursors such as methane and carbon monoxide as well as aerosol sources that have a high proportion of black carbon (BC). BC certainly is not the 'most effective way of slowing global warming', but achievable near-elimination of anthropogenic BC sources would help minimize expected warming from reduced sulfate emissions, while restoration of near-pristine snow and ice albedos would reduce climate change in particularly climate-sensitive regions.

JEFFREY T. KIEHL (National Center for Atmospheric Research) discussed coupled chemistry-climate modeling.The chemical system of the atmosphere is determined by surface emissions, atmospheric transport and removal processes. A natural link between the chemical system and the climate system is through the hydrologic cycle. Changes in large-scale circulation patterns and precipitation patterns could alter the distribution of a number of chemical constituents. The formation of aerosols and their effects on the radiative budget of Earth also provide connections between the chemical and the climate system. To investigate the sensitivity of the chemical system to climate change, NCAR carried out a number of coupled climate-chemistry simulations. In these simulations, where aerosol emissions are changed, only the direct radiative effect of aerosols and their uptake of chemical species are considered. NCAR results show that, at the global scale, a decrease in emissions produces a warmer and moister climate due to the reduction in albedo. In addition, the tropospheric burdens of OH and ozone increase when aerosol emissions are decreased. The ozone response is a combination of the impact of reduced heterogeneous uptake of N_2O_5 and increased ozone loss in a moister atmosphere. Under reduced aerosol emissions, the tropospheric burden of NOx ($NO+NO_2$) is strongly reduced by an increase in nitric acid formation but also increased by the reduced N_2O_5 uptake. These results indicate that there are non-negligible coupling effects between the chemical and climate systems. These effects would be enhanced if the indirect aerosol effects on the climate system were included. Including the effects of aerosols on photochemistry is an additional feedback that needs further exploration in NCAR modelling studies.

JOYCE E. PENNER (University of Michigan) discussed the factors contributing to uncertainties in aerosol forcing from fossil fuel emissions and from biomass burning. Direct aerosol forcing uncertainties arise because the processes determining aerosol optical depth are poorly represented in models. This is due to uncertainties in aerosol sources, in representing the processes that determine the aerosol lifetime in global models, and in

determining the optical properties associated with the aerosols. Differences between measurements and models are largest for dust, black carbon and organic matter. The difference between measured and modeled optical depths is associated with an error of order 2 W m^{-2}. The vertical distribution of aerosols differs greatly between models and is, so far, poorly constrained by measurements, but comparison of the models with Stratospheric Aerosol and Gas Experiment (SAGE) measurements suggests that dust is overestimated in the upper troposphere in most models. The sources of biomass aerosols have been thought to be very uncertain, but progress has been made by combining bottom-up and top-down (inverse) methods of determining these highly variable sources. A recent study of the uncertainties associated with first indirect forcing estimates indicates that the largest uncertainties are associated with uncertain knowledge of the aerosol size distribution, the cloud fraction, the aerosol burden (which depends on emissions and the aerosol lifetime), the updraft velocity parameterization, and the treatment of the dispersion of cloud droplets. The parameterization of the second indirect effect in global models is difficult because the basic relative humidity and cloud fields are not well constrained. Progress is needed in improving the parameterizations on which these fields depend as well as the measurements used to constrain the models.

VEERABHADRAN RAMANATHAN (Scripps Institution of Oceanography/University of California, San Diego) discussed the effects of absorbing aerosols on the surface and atmospheric radiative forcing, and described their regional and global impacts on climate and the hydrological cycle. He showed results of several field measurements that reveal the large reduction of solar radiation at the surface, i.e., "global dimming", by absorbing aerosols emitted to the atmosphere by human activities. These aerosols are transported over many regions of the planet including over oceanic regions and hence are referred to as Atmospheric Brown Clouds (ABCs). ABCs lead to as much as 5% to 15% seasonal average reduction of surface radiation over large regions of the tropics including the Indian, Pacific and Atlantic oceans. These reductions are accompanied by increased solar heating of the atmosphere. The surface cooling, accompanied by atmospheric heating, perturbs the hydrological cycle in significant ways, leading to decrease in rainfall and drying. In addition, the surface cooling resulting from the decrease of solar radiation at the surface may have masked as much as 50% of the greenhouse warming in the tropics.

STEPHEN E. SCHWARTZ (U.S. Department of Energy/Brookhaven National Laboratory) pointed out that the atmospheric concentration of carbon dioxide is expected to double its pre-industrial value during the present century. The resultant long-wave radiative forcing is expected to increase global mean temperature, but the magnitude of this increase is quite uncertain, in large part because of uncertainty in Earth's climate sensitivity, the change in global mean temperature that would result from a given change in global mean radiative flux. Current estimates of this sensitivity indicate a temperature increase from CO_2 doubling ranging from 1.5 to 4.5 °C; sensitivity at the high end of this range would lead to a temperature increase comparable to that between the glacial ice ages and the present temperate period, 6 °C. Approaches to estimate Earth's climate sensitivity include use of climate models and empirical estimates based on the increase in temperature over the industrial period. However for both approaches it is essential to take into account other forcings that have occurred over this period, most importantly forcings due to increases in concentrations of atmospheric aerosols. Increased concentrations of aerosol particles, which scatter light and serve as the seed particles on which cloud droplets form, exert a cooling

influence on climate by increasing planetary reflectance, thereby decreasing the amount of incident solar energy that is absorbed by the Earth-atmosphere system. The climate forcing of anthropogenic aerosols is thought to be comparable in magnitude to that of the increased greenhouse gases but is much less accurately known. This forcing thus offsets an uncertain but perhaps substantial fraction of the warming influence of increased greenhouse gases. If the aerosol offset to the greenhouse gas forcing is substantial, Earth's climate sensitivity maybe much greater than is indicated by the warming that has occurred thus far over the industrial period. In order to meaningfully determine Earth's climate sensitivity from changes in forcing and global mean temperature over the industrial period, these quantities must be known to uncertainty of 20% or better. This requires a reduction in the uncertainty in aerosol forcing to less than 0.5 W m^{-2}, at least a factor of three reduction from the present estimates of this uncertainty. Central to determining aerosol forcing is modeling the concentrations and microphysical properties of anthropogenic aerosols. Key research requirements include developing emissions data bases for aerosols and gaseous precursors of accuracy compatible with the accuracy requirements in aerosol forcing, and acquiring understanding and model-based representation of the processes responsible for production, microphysical and chemical evolution, and removal of aerosol constituents and for the influence of these particles on cloud microphysical processes and properties.

JOHN H. SEINFELD (California Institute of Technology) presented results of GCM simulations of 2000 and 2100 equilibrium climate corresponding to present and projected greenhouse gas concentrations. Simulations were carried out with the Goddard Institute for Space Studies GCM II'. The 2100 climate was based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) A2 emissions scenarios[1]. Embedded within the 2000 and 2100 equilibrium climates were ozone and aerosol concentrations generated from ozone and aerosol precursor emissions corresponding to each of those dates. These simulations had the goal of exhibiting the effect of a future (greenhouse forced) climate on ozone and aerosol levels. These simulations can be viewed as the first step toward a fully coupled simulation in which ozone and aerosols are fed back into the climate. He also presented results of a one-hundred-year climate simulation of black carbon. The goal was to understand the effect on climate of black carbon increases since pre-industrial time. He investigated the effect on surface temperature of the state of mixing of the black carbon with sulfate aerosol. Uncertainties associated with the climatic effect of the atmospheric state of black carbon were identified.

DANIEL J. JACOB (Harvard University) discussed the climatic effects of tropospheric ozone, the current understanding of background tropospheric ozone, and the potential effects of climate change on ozone. Global radiative forcing from tropospheric ozone since pre-industrial times could have been as low as 0.2 W m^{-2} or as high as 0.8 W m^{-2}, a range of uncertainty much larger than acknowledged by IPCC [2001] and reflecting our poor understanding of the main natural sources of tropospheric ozone (lightning, fires, soils, stratosphere-troposphere exchange). Although tropospheric ozone is a less efficient warming agent per unit forcing than CO_2, its impact is felt disproportionably in the northern

[1] A2. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

hemisphere and it also causes large stratospheric cooling in the Arctic. Current understanding of the factors controlling background tropospheric ozone has been challenged by observed increases over Europe and North America over the past few decades that are in their ensemble at odds with current models. Better understanding of this background is critical not only for projections of future ozone radiative forcing, but also for meeting air quality standards to protect health and vegetation. Decreasing methane emissions could be of major benefit both for climate forcing and for decreasing the ozone background. Strong sensitivity of ozone to future climate change is demonstrated by the observed relationship of ozone to temperature. Increasing duration of stagnation events is expected over the 21st century as a result of decreasing cyclone frequencies, leading to more severe pollution episodes.

JENNIFER A. LOGAN (Harvard University) discussed the effects of major fires on air quality, observed trends in boreal fires, the linkage between fires and weather, and approaches to modeling fires in a future climate. There have been several examples in recent years of major fires having a deleterious effect on air quality, especially CO and particulate loading. Fires in Siberia in 1998 perturbed air quality throughout the northern mid-high latitudes; 2002 and 2003 were also severe fire seasons in boreal Russia, while there were record fires in Alaska in 2004. Fires are most likely to occur in hot weather with low humidity, when surface fuels are dry. The area burned in North America varies considerably from year to year, and in any given year, the very large fires contribute primarily to the total area burned. There has been a large increase in area burned in Canada since 1970 that has been attributed to temperature increases. The relationship between fires and climate has been explored by looking at statistical relationships between fire areas and meteorological variables, including drought indices. Assessment of the effects of future climate on fires has been done with General Circulation Models (GCMs), and has generally focused on predicting the effects of doubling or tripling of atmospheric CO_2 on fire severity or fire potential. Past work suggests an increase in fire severity of 10-50% for the U.S. and Canada, an increase in the length of the fire season, and large regional variations in the change in fire severity. These are likely underestimates as they do not allow for a change in ignition frequency, from lightning for example. Statistical relationships with meteorological variables can explain 35-65% of observed interannual variance of area burned in Canada and the western U.S., and these relationships will be used at Harvard, in combination with model simulations of the future climate using the GISS model, to develop scenarios for fire emissions. A warmer climate in also likely to lead to increases in fuel consumption in boreal fires, and surface fuels dry out more. A major uncertainty in assessing the effect of fire emissions on air quality relates to the altitudes at which the emissions are injected to the atmosphere. Measurements of plume heights made by the Multiangle Imaging SpectroRadiometer (MISR) instrument on the Terra satellite offer great promise in this area. Another uncertainty lies with limited measurements of emission factors for nitrogen oxides. There is also a need for an improved, coherent data base for fire statistics in the U.S., and for greater interaction between experts in the fire community, and the atmospheric chemistry community. Finally, improvements in the hydrologic cycle in GCMs are required for fire prediction, which depends on precipitation amounts and frequency, as well as humidity.

S. TRIVIKRAMA RAO (National Oceanic and Atmospheric Administration/U.S. Environmental Protection Agency) discussed the effects of changing climate on ambient air quality. Using the results of global-to-regional modeling performed by different research groups in the country, he illustrated that global climate change can alter the synoptic flow patterns and

summertime extreme temepratures, which, in turn, could lead to increases in ozone levels in the eastern US and increases in adverse health effects. Since the regional modeling done to date did not consider the feedback effects of ozone and aerosols on radiation, boundary-layer dynamics, photolysis rates, cloud attenuation, etc. there is a critical need to develop models that can properly treat these feedback mechanisms to better chracterize climate change-air quality interactions. He suggested some research topics deserving immediate attention to help improve our understanding of the climate change and its implications to future air quality.

WILLIAM F. FITZGERALD (University of Connecticut) considered important features of the atmospheric and aquatic cycling of Hg, the linkages between these major components of global mercury (Hg) cycle, and the potential effects of climate changes on the behavior and fate of Hg in the environment. Production and bioaccumulation of methylmercury (MeHg), a neurotoxin, in aquatic ecosystems is the primary Hg related environmental and human health concern. Human exposure to MeHg occurs principally from the consumption of fish, mostly of marine origin. MeHg production, which occurs primarily in sediments in both terrestrial and marine aquatic ecosystems, is related directly to the availability/loadings of Hg, especially atmospheric. Thus, climate changes that affect (1) Hg loadings will affect the production and accumulation of MeHg in aquatic ecosystems, and (2) the in-situ production or destruction of MeHg will affect its accumulation in the biosphere. Coastal marine regions need special attention because production in near-shore sediments may be the principal source of MeHg to the oceans and its biota, and the biogeochemical cycling of Hg and MeHg in marine systems is poorly understood. Elemental Hg (Hg^o) cycling and emissions to the atmosphere are major features of the biogeochemistry of Hg in both fresh and marine waters. More than 95% of the total Hg in the atmosphere is in the elemental form, and its oxidation to ionic mercuric (Hg^{2+}) with subsequent deposition is the major removal mechanism for atmospheric Hg. Oxidation of Hg^o is evident (i.e., particulate and reactive gaseous mercury, RGM, species) in high latitudes coinciding with polar sunrise, and more generally, in the marine boundary layer. Atmospheric measurements suggest that Arctic mercury depletion events (MDEs) could be responsible for large enhancements in the deposition of Hg to sensitive Arctic aquatic ecosystems. There has been little research, however, regarding the net effect of MDEs to these systems through examination of Hg fluxes and cycling in lakes or marine systems in the affected regions. Moreover, studies of chemical cycling in the marine boundary layer should be encouraged both in support of oceanic studies but also as a specific examination of the interplay among Hg oxidants, e.g. hydroxyl (OH) radical, bromine (Br) radicals, and ozone (O_3). Atmospheric Hg^o oxidation in high latitudes and over the oceans is likely to be similar from a mechanistic view. Improved understanding of these mechanisms and processes will aid in modeling (i.e., predicting and evaluating) the potential effects of climate change on the global cycling of Hg and MeHg.

RONALD G. PRINN (Massachusetts Institute of Technology) discussed the general goals and concepts of earth system modeling using, as an example, the MIT Integrated Global System Model (IGSM). The IGSM consists of a set of coupled submodels of economic development and its associated emissions, natural biogeochemical cycles, climate dynamics, air pollution, and natural ecosystems. It is specifically designed to address key questions in the natural and social sciences that are amenable to quantitative analysis and are relevant to environmental policy. Urban air pollution and climate are closely connected due to the shared generating processes for emissions and the shared atmospheric chemistry of air pollutants. Thus policies

designed to address air pollution may impact climate and vice versa. The IGSM is used to illustrate some of the connections by considering caps on emissions of nitrogen oxides (NOx), carbon monoxide (CO), volatile organic compounds (VOC), and sulfur oxides (SOx) both individually and combined. These caps can lower ozone causing less warming, lower sulfate aerosol concentrations yielding more warming, lower hydroxyl (OH) radical concentrations and thus increase methane (CH_4) levels giving more warming, and finally, allow more carbon uptake by ecosystems leading to less warming. Overall, these effects significantly offset each other suggesting that air pollution policy has a relatively small net effect on the global mean surface temperature and sea level rise. However, this study does not account for the effects of air pollution policies on overall demand for fossil fuels and on the choice of fuels (coal, oil, gas), nor does it consider the effects of caps on black carbon or organic carbon aerosols on climate. These effects, if included, could lead to more substantial impacts of capping pollutant emissions on global climate than concluded above. Caps on aerosols in general could also yield impacts on other important aspects of climate such as the regional patterns of cloudiness and precipitation.

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