U.S.–India Collaboration on ... and

Large-scale interest in air quality management and climate research continues to grow in developing countries due to the rising trends in air pollution and greenhouse gas emissions. The rapid growth of the Indian economy, spurred by industrial and urban expansion, has been accompanied by environmental stresses in both urban and rural areas, particularly in air quality. The current capacity in India in research, education, and operational aspects of air quality measurements, modeling, forecasting, and regulatory management needs further enhancement.

Air Quality Climate Research and Education

With partial support from the U.S. National Science Foundation and U.S. Department of Energy, a workshop held March 14–24, 2011, in India, brought together experts from the United States and India (among other countries) with a common vision for identifying priority areas of research and development in the air quality-climate arena, and a commitment to sustaining long-term Indo-U.S. collaboration.

The workshop began with three days of invited lectures and presentations. This was followed by a seven-day hands-on training on a publicly available suite of numerical atmospheric models that are used worldwide in a variety of air quality applications, from basic research to local- and regional-level planning and management. Such models are useful for assessing the nature and magnitude of air pollution, and are helpful in formulating innovative emission control policies. The training included concepts of atmospheric chemistry and physics, the Sparse Matrix Operator Kernel Emissions (SMOKE) model, the Weather Research and Forecasting (WRF) model, and the Community Multiscale Air Quality (CMAQ) model.

The workshop helped improve understanding of the emission sources and meteorological conditions that contribute to regional- and urban-scale air quality and climate issues of relevance to protecting public health and the environment in India. The workshop was Phase I of a two-phase joint U.S-India research initiative. Phase II will improve scientific understanding of air quality and climate in the region, with emphases on assessing the future of air quality in the tropics and on linkages between air quality and climate change.

Introduction

The United States has made significant advances in confronting environmental challenges by developing the scientific and technological basis for air quality measurements, atmospheric modeling and analysis, and policies for mitigation over the past few decades. However, given the global nature of environmental concerns (e.g., the global distribution of long-lived species such as carbon dioxide, methane, and mercury, the intercontinental transport of short-lived pollutants such as ozone and aerosols, global climate change), the scope of these scientific advancements needs to be expanded. In particular, major air quality studies in the United States have focused primarily on U.S. emissions and meteorology. More attention needs to be focused on tropical/subtropical regions such as South Asia, which are projected to contribute significantly to the global pollution burden.[1]

India has been cited as one of the five fastest-growing economies in the world. This growth has resulted in concerns regarding its impact on the environment, in particular the impact of air pollution on climate and human health. The explosion of vehicular traffic in both urban and rural areas, as well as the rapid transition from a predominantly agricultural to a mixed agro-industrial economy has led to adverse environmental impacts.[2] Recognizing this, India had enacted policies to limit or prevent these impacts on the environment, climate, and human health. From the perspective of air quality science, the challenges are to accurately characterize the chemical processes in the regional environment and their responses to the prevailing meteorological conditions, and to quantify the emissions from the responsible sources and their representation in current photochemical modeling applications over the tropical region.

Air Quality in Southeast Asia: An Emerging Need

Global air quality science has proven effective in risk reduction (for both human health and the environment), and climate change mitigation in the United States.[3,4] Understanding and developing air quality science has become a pressing need in the tropical regions of the world as well, as they are undergoing rapid industrializations due to unprecedented economic development. Aspects of air quality related to gaseous and particulate

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species are also strongly linked to climate perturbations, thus posing a complicated challenge, especially for Asia and its peoples and their sustenance related to the energy, transport, agricultural, and water sectors.[5-10]

For example, India's recent economic growth has led to a rapid increase in aviation activity during the past decade; India's domestic air traffic has almost doubled in the past five years,[11] and it is expected that India will be the third largest aviation market within 10 to 15 years, with a projected three-fold increase from 2010 to 2020.[12] Results from recent work in the United States in the air transport sector are instructive for India's situation. Woody et al.[13] showed that if aviation activity in the United States were to grow by a factor of 2.24 from 2005 to 2025, emissions due to landing and takeoff activities would lead to a quadrupling in aviation-related fine particulate matter concentrations, and Levy et al.,[14] using the Woody et al. data, found that aviation-related adverse health impacts over the same time period would increase in the United States by a factor of 6.1. Although aviation emissions are currently a small percentage of India's overall anthropogenic emissions budget, the impacts of aviation activity on future-year air quality in India will likely be even more significant than those shown in the U.S.-based study.

It is now well established that the current levels of particulate matter (PM) in the United States account for some 40,000 premature mortalities annually, with many more hospital admissions being attributed to both high ozone and high PM levels. These health outcomes are now understood to be due to, or at least highly correlated with, a complex of specific weather patterns, climate variability, and air quality.[15] The rapid economic growth in Indian cities over the past decade, together with their unique atmospheric chemical constituents (very high carbonaceous PM levels) and meteorology, have given rise to more severe problems related to air quality than are seen in most other regions in the world. In 2005, more than 50 Indian cities exceeded the U.S. National Ambient Air Quality Standards (NAAQS) for annual average respirable suspended particulate matter (RSPM) concentration of 15 $\mu g/m^3$ by factors of 6 or more (the India NAAQS for annual average RSPM concentration is 60 $\mu g/m^3$).[16]

Serious health impacts imposed on the populations by the ambient air quality in several Indian cities, including Delhi, Pune, Hyderabad, Chennai, and Bangalore, have been documented. This poses a critical need for efficient and reliable means to better understand the atmospheric chemistry and meteorological conditions that contribute to the urban pollutant mix. This can best be addressed by using advanced decision support systems to help identify effective mitigation strategies; such systems include source-based, multiscale, multi-pollutant modeling; relevant observational databases; and advanced analysis tools to evaluate the performance of models against observations using approaches recommended by Dennis et al.[17,18] The insights gained in this type of effort in India are expected to benefit from the continued enhancement of tools and technologies for environmental decision-making in the United States.

In the United States and many other developed countries, atmospheric research on urban- and regional-scale air quality has focused on understanding ozone and secondary PM formation and transport during episodic pollution events over scales of tens to hundreds of kilometers. Concerns with environmental justice and deliberate and accidental releases of air toxics have spurred research into dispersion of primary pollutants from scales of several meters to over hundreds and even thousands of kilometers from the release. These concerns are pertinent to India as well. Several field studies have been conducted to understand pollutant dispersion in urban areas in India. Indian scientists have made progress in several areas of modeling, including dispersion under low-wind-speed conditions typical of urban areas, and modeling of accidental releases.[19]

The scientific expertise available within the Indian air quality research community, as evidenced in numerous studies, offers a valuable resource for future collaborative research among Indian and U.S. scientists. For example, the Indian Ocean Experiment (INDOEX) of January–March 1999 described by Ramanathan et al.[20] led to the publication of several seminal papers on the impacts of the Indian subcontinental pollutant plume not only on air quality, but also on climate change and variability in the region, and on the issues of identifying and characterizing the sources responsible.[21,22] The findings of INDOEX are still emerging (e.g., regarding the role of South Asian aerosol, including black carbon, on the formation of atmospheric brown "clouds" that cause global dimming[23,24]).

The INDOEX field campaign also led to successive refinements of the regionally relevant high-resolution

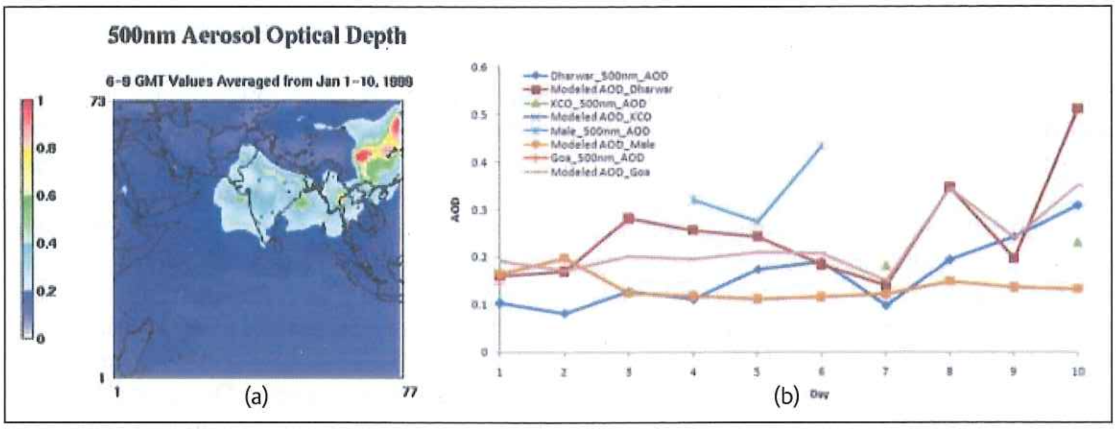

Figure 1. (a) Spatial pattern of aerosol optical depth (AOD) predicted by METCHEM in the 350–700-nm wavelength band, comparable to the 500-nm AERONET observations; (b) comparison of modeled AOD at Dharwar, Kashidoo Climate Observatory (KCO), Male, and Goa, India, for the period January 1–10, 1999, against available observations from AERONET. Trend lines are shown for ≥ 3 data points in the station observations. Modeled AODs at KCO and Male are indistinguishable due to the close proximity of these sites.

emission inventories to drive these models that started with Reddy and Venkataraman.[25,26] Regional-scale modeling studies conducted by Shankar et al.[27] using the Reddy and Venkataraman inventory to drive a coupled meteorology-chemistry model clearly showed the continental plume off the South Indian coast after only a two-week simulation period in January 1999; Figure 1 (a) shows the spatial distribution of the resulting aerosol optical depths (AODs) and (b) shows the AOD trends for this period under future emissions scenarios (IPCC scenarios A1B and B2), compared to current conditions.

U.S.–India International Workshop

It is clear therefore that India and the United States have many common interests and needs in this arena, and that joint efforts can benefit both countries, as well as other regions of the world. To help address the challenges arising from air pollution over South Asia, the "U.S.–India International Workshop on Air Quality: Collaborative Science, Research, and Education in Air Quality Measurements, Modeling, and Analysis" was organized by a team of atmospheric scientists from North Carolina State University (NCSU), the University of North Carolina at Chapel Hill (UNC), and the U.S. Environmental Protection Agency.

The workshop was convened at the Administrative Staff College of India (ASCI), in Hyderabad, India, during March 14–24, 2011. The workshop included invited lectures and presentations by Indian, American, European, and other overseas scientific experts in the field, and provided an opportunity to share information and discuss the key scientific issues and challenges to addressing India's air quality needs. Approximately 250 participants from six countries attended the workshop. Its outcome was a prioritized list of research areas and a concrete road map for collaborative research endeavors.

The workshop also included hands-on operational training on the use of a publicly available air quality modeling system (see Figure 2) consisting of the Sparse Matrix Operator Kernel Emissions (SMOKE) processing system,[28] the Weather Research and Forecasting (WRF) model,[29] and the Community Multiscale Air Quality (CMAQ) model,[30] preceded by a detailed overview of the atmospheric chemistry and physics involved in their formulations. Additional information on this workshop is available online at www.asci.org.in/aqccw/index.html.

The workshop provided an improved understanding of the air quality science underlying the regional- to global-scale air quality and climate issues of relevance to public health and the environment in Southeast Asia. The discussions and presentations provided insights into the prevailing meteorological patterns and chemical regimes, and the model formulations required to capture their characteristics to reliably assess air quality in the region. Emission source information, as well as insights on regional circulations provided by Indian participants, greatly contributed to the knowledge gained and disseminated through the workshop.

Research topics discussed during the workshop included:

Meteorology
- urban canopy parameterization;
- modeling of clouds and precipitation, especially in the monsoon seasons;
- land-sea breezes in coastal cities; and
- long-range transport (i.e., north-south flow that transports pollutants from source regions to remote-rural areas).

Emissions
- spatial and temporal emissions inventory from agricultural activities, both crop and animal;

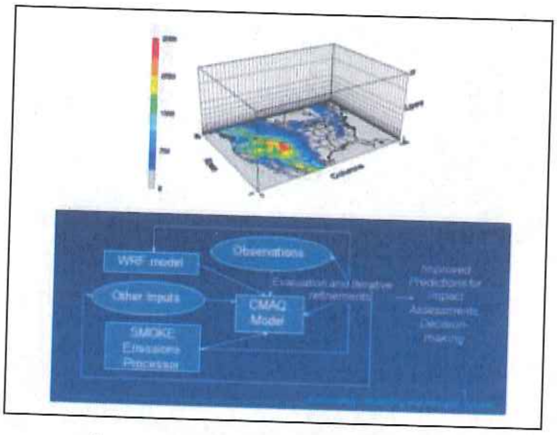

Figure 2. Flow diagram of the WRF-SMOKE-CMAQ modeling system distributed by the CMAS Center for research and regulatory applications. Also shown is an example modeling grid (color scale represents terrain height in meters).

- inventory of pollutants from key source sectors: emissions of PM from paved and unpaved roads, which is of particular concern in Indian cities;
- emission factors for various sources of black carbon (BC): There is strong evidence regarding the contributions of domestic biofuel combustion and agriculture burning in India to the observed BC budget, identified as a significant component of regional climate forcing;
- vehicular emissions in urban areas such as Hyderabad, Bangalore, Chennai, Mumbai, Kolcuta, and Delhi, particularly due to the increased use of two- and three-stroke engines;
- temporal allocation, particularly in the combustion of biomass from crop waste, another major contributor to the regional BC budget;
- chemical speciation, for soil-derived dust, and for fly ash, a large source of primary PM in India;
- chemical speciation of diesel vs. alternative fuels for sensitivity studies in urban areas;
- evolution of anthropogenic emissions under emerging regulations;
- sensitivities of emissions to alternative fuel technologies;
- impacts on emissions in the domestic source sector of pilot projects that have been undertaken to promote clean cook stove technology;
- impacts of vehicular emissions of cleaner alternatives than diesel fuel, such as compressed natural gas; and
- development of top-down vs. bottom-up emissions inventories to support air quality modeling studies, with case studies.

Pollutant chemistry and transport

- gas-, aqueous-, and particulate-phase chemistry, and geographic and seasonal differences in chemical regimes;
- atmospheric processes (advection, diffusion, transformation, deposition) contributing to urban pollutant mix;
- fine-particle formation associated with photochemistry; and
- integrated measurement and modeling studies to perform source attribution.

Air quality modeling

- specification of lateral boundary conditions for limited-area modeling;
- chemical mechanisms to examine very low observed ozone in South Asia; and
- interactions of meteorology and atmospheric chemistry (i.e., aerosols, radiation, clouds, and precipitation).

Air quality model applications

- sensitivities to lateral boundary conditions; horizontal and vertical grid resolution; chemical solvers; numerical schemes; model time step;
- retrospective analyses to show application of air quality models for effective policy-making, using a case study;
- routine operational applications; optimization techniques;
- research studies in India; and
- future-year modeling, including the interactions of climate and air quality, and dispersion of pollutants within urban areas.

Assessing the Future of Air Quality in the Tropics

The workshop was Phase I of a two-phase initiative. Phase II will contribute toward more in-depth scientific understanding of air quality and climate in the region, as discussed below.

***Future scientific collaborations*:** The Phase I workshop's primary goal was to bring together experts in the field of air quality and meteorological science from India and the United States to forge collaborations that will explore fundamental scientific challenges in this field, especially as it relates to urban-, regional-, and global-scale processes. In Phase II, a list of specific, highly relevant topics for scientific research will be generated and proposals will be submitted to U.S. and Indian funding agencies. The phased initiative will lay the groundwork for the subject areas and the order of priority of the challenges to be tackled via multiple research projects.

***Enhancement of scientific, and educational activities*:** A key scientific contribution of this initiative will be to assess the state of the art in air quality management in India, and to develop a set of recommendations for possible improvements, which would exploit recent advances reported in the scientific literature that are relevant to air quality issues in India. The assessment and recommendations could then be used by appropriate organizations/agencies that are involved in air quality management in India, both at the central and local/regional levels, to take concrete actions toward improvements.

On the educational front, the training program that began in India as part of the Phase I workshop will enable a new generation of scientists drawn from various government, business, and educational organizations in India to become proficient in atmospheric chemistry and climate science, and in the use of three state-of-the-science models (WRF, SMOKE, and CMAQ) to understand scientific issues related, respectively, to regional- and urban-scale meteorology, trace species emissions, and air quality. The UNC members of the workshop team serve as senior staff at the EPA-sponsored Community Modeling and Analysis System (CMAS) Center (www.cmascenter.org), which promotes and facilitates the use of its component models and tools by a growing user base worldwide.[31] The expertise of the emerging generation of modelers in India will continue to be fostered through the CMAS user support and training infrastructure.

Linkages Between Air Quality and Climate Change

A key component of this U.S.–India joint research initiative is the study of how climate change and air quality are linked. This topic will be a primary focus of Phase II. An emerging challenge in the science of air quality is to improve scientific understanding of its important linkages to climate change through the interaction of specific gas- and particulate-phase species with solar radiation. Changes in emissions of primary or precursor pollutants can result in increases or decreases in some of these radiatively important species (e.g., ozone and sulfate aerosol); these substances, in turn, can exert a positive or negative forcing on climate, depending on their radiative impacts. The multiplicity of these pollutants in the ambient air thus poses a correspondingly complex challenge in formulating mitigation measures that simultaneously address their adverse impacts on air quality and climate.

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The Indian air quality issue and its links to climate are juxtaposed with corresponding challenges in the entire Asiatic region,[32] and have relevance in the global dimension. Thus, the key scientific considerations for air quality in India include quantifying the agents causing the air quality problems, understanding and interpreting their observed trends, and assessing the potential future trajectories in response to various emissions abatement strategies.

The corresponding climate question to be addressed in Phase II of this joint research venture is this: How does the evolving atmospheric composition under current and projected emissions growth scenarios relate to the climate forcing of key gaseous and aerosol species, and what are the resulting societal impacts on regional to global scales—for example, heat waves, changes to monsoon patterns resulting in droughts and floods, and the impacts of those changes on food and water security in geographically similar parts of the world? **em**

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