U.S. – India Collaboration on Air Quality and Climate Research and Education

Viney P. Aneja* and Anantha Aiyyer
Department of Marine, Earth, and Atmospheric Sciences
North Carolina State University
Raleigh, NC, 27695-8208, USA

Adel Hanna, Uma Shankar, Zachariah Adelman, and Saravanan Arunachalam
Institute for the Environment
University of North Carolina at Chapel Hill
Chapel Hill, NC 27599-6116, USA

S. Trivikrama Rao, Rohit Mathur, and J. David Mobley
Atmospheric Modeling and Analysis Division
National Exposure Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711, USA

V. Ramaswamy
National Oceanic and Atmospheric Administration
Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA

V. Murali Krishna and Valli Manickam
Administrative Staff College of India,
Hyderabad, Andhra Pradesh, India

M.P. Singh, Jhumoor Biswas and Era Upadhyay
Ansal Institute of Technology
Gurgaon, India

*Corresponding Author
Telephone: (919) 515 7808
Email: VINEY_ANEJA@NCSU.edu

For publication in: EM, Air and Waste Management Association
July 2011

Abstract

The rapid growth of the Indian economy, spurred by the industrial and urban expansion has been accompanied by environmental stresses, 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 management is a growing problem in both the urban and rural areas in India. A workshop, with partial support from the U.S. National Science Foundation brought together several experts from the U.S. and India with a common vision for identifying priority areas of research and development in the air quality-climate arena, and a commitment to sustain long-term Indo-US collaboration, during March 14-24, 2011 in India (Phase I). To engage participation by emerging scientists in the field, the workshop included three days of invited lectures and presentations, followed by a 7-day hands-on training on a publicly-available suite of numerical models that are used world-wide in a variety of air quality applications from basic research to local- and regional-level planning and management. The training included concepts of Atmospheric Chemistry, Sparse Matrix Operator Kernel Emissions (SMOKE) model, Weather Research and Forecasting (WRF) model, and the Community Multiscale Air Quality (CMAQ) model. This workshop helped improve understanding of the emission sources and meteorological conditions that contribute to regional-to-urban-scale air quality and climate issues of relevance to protecting public health and the environment in India. Phase II will contribute towards a scientific understanding of air quality and climate in the region. Large-scale interest in air quality management and climate research is incessantly growing in the developing countries due to the increasing trends in air pollution and greenhouse gas emissions; and they are estimated to grow in coming years. Atmospheric models are useful for assessment of the nature and magnitude of the air pollution. The model studies help in formulation of innovative emission control policies for protecting human health and the environment.

1. 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, 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 CH_4, Hg and CO_2, the inter-continental transport of short-lived pollutants, and global climate change), the scope of these scientific advancements needs to be expanded. In particular, major air quality studies in the U.S. have focused primarily on extra-tropical urban emissions and meteorology. Limited attention has been focused on tropical/sub-tropical regions such as South Asia which are projected to contribute significantly to the global pollution burden (Ramanathan and Carmichael, 2008).

India has been cited as one of five fastest growing economies in the world, but this growth has become increasingly attended by 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 (Aneja et al., 2001a). From the perspective of air quality science, the challenges are to accurately characterize the chemical processes in the regional environment, and their response 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.

2. Air Quality in Southeast Asia: An Emerging Need

The development of air quality science in the tropical regions of the world, especially with increased industrial activities owing to increasing economic development is rapidly becoming an emerging need; since global air quality science is increasingly being cited as a critical aspect of risk reduction and climate change mitigation in the U.S. (West et al, 2006; Tagaris et al, 2007). Elements associated with air quality issues (e.g., gas and particulate species) are also inextricably linked to climate perturbations, thus posing a complicated challenge and especially for Asia and its peoples and their sustenance related to the energy, agricultural and water sectors (Aneja et al., 2001b; Aneja et al., 2008; Aneja et al., 2009; Ramaswamy, 2009; Horton et al., 2010). Moreover, recent work in the United States has shown that emissions due to landing and takeoff activities from a sample growth in aviation activity by a factor of 2.24 in the U.S from 2005 to 2025 leads to a 4-fold increase in aviation-related $PM_{2.5}$ concentrations (Woody et al, 2011). Furthermore, aviation-related adverse health impacts would increase by a factor of 6.1 from 2005 to 2025, with a factor of 2.1 attributable to emissions, a factor of 1.3 attributable to population factors, and a factor of 2.3 attributable to changing non-aviation concentrations which enhance secondary $PM_{2.5}$ formation (Levy et al, 2011). India's recent economic growth has also led to a rapid increase in aviation activity during the past decade. It is expected that India will be the third largest aviation market within 10-15 years, with a projected 3-fold increase from 2010 to 2020 (ACI, 2011). Though aviation emissions are a small percent of the overall anthropogenic emissions budget, given the findings from the U.S. based study, the impacts of aviation activity on future year air quality in India will be likely even more significant.

It is now well established that the current levels of particulate matter (PM) in the U.S. account for some 40,000 premature mortalities annually, with many more hospital admissions being attributed to both high ozone and 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 (Hanna et al., 2011). 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 seen in most other regions in the world. It should be noted that in 2005 more than 50 Indian cities exceeded the U.S. National Ambient Air Quality Standards for annual average Respirable Suspended Particulate Matter (RSPM) concentration of $15\mu g/m^3$ by factors of 6 or more, with Delhi and Pune being among the top 35 (Aneja 2001; Narain, 2008, Government of India, 2009). Serious health impacts imposed on the populations by the ambient air quality in several Indian cities such as Delhi, Pune, Hyderabad, Chennai, and Bangalore have been documented. This poses a critical need for efficient and reliable means to examine and better understand the atmospheric chemistry and meteorological conditions that contribute to the urban pollutant mix. These can best be achieved through the use of advanced decision support systems that include source-based multi-scale 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. (2010), and help identify meaningful and effective mitigation strategies. The insights gained in this effort are expected to benefit from the continued enhancement of tools and technologies for environmental decision-making in the U.S.

In many developed countries, atmospheric research in urban-to-regional air quality has focused on understanding ozone and secondary particulate matter (PM) formation and transport during episodic pollution events over scales of tens to hundreds of kilometers. New concerns with environmental justice and deliberate and accidental release 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. Several field studies (Allwine et al., 2001; Venkatram et al., 2004,) have recently 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 (Kesarkar et al, 2007). The Indian Ocean Experiment (INDOEX) of January – March 1999 described by Ramanathan et al. (2001) led to the publication of several seminal papers in the literature on the impacts of the Indian sub-continental plume on not only air quality but on climate change and variability in the region and on the issues of identifying and characterizing the sources responsible (Novakov et al., 2000; de Laat et al., 2000; Guazotti et al., 2001; Mayol-Bracero et al., 2002; Reddy et al., 2004; Venkataraman et al., 2005). The findings of INDOEX are still emerging, e.g., regarding the role of South Asian aerosol, including black carbon (BC), on the formation of atmospheric brown "clouds" that cause global dimming (Ramanathan and Crutzen, 2003, Ramanathan and Carmichael, 2008). This field campaign not only spawned many global modeling studies focused on the South Asian aerosol forcing on climate (e.g., Satheesh and Srinivasan, 2002), but also led to successive refinements of the regionally-relevant high-resolution emission inventories to drive these models that started with Reddy and Venkataraman (2000a, b). Regional-scale modeling studies conducted by Shankar et al. (2005) using the inventory of Reddy and Venkataraman (2000a,b) to drive a coupled meteorology-chemistry model clearly showed the continental plume off the South Indian coast even after a 2 week period in January 1999; Figure 1 (a) shows the spatial distribution of the resulting aerosol optical depths (AODs). Figure 1(b) shows the AOD trends for this period under future emissions scenarios (IPCC scenarios A1B and B2) compared to current conditions. Since then research has continued over South Asia with measurement and modeling studies to improve BC emissions estimates for the region (Bond et al., 2004; Venkataraman et al., 2005, 2006; Habib et al., 2008). The scientific expertise available within the Indian air quality research community as evidenced by these and numerous other studies offers a valuable resource for future collaborative research among Indian and U.S. scientists.

3. U.S.-India International Workshop

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 US Environmental Protection Agency as Phase I of a two-phase collaboration. 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. About 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 shown in Figure 2 to interested participants consisting of the Sparse Matrix Operator Kernel Emissions (SMOKE) processing system (Houyoux et al, 2005), the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008), and the Community Multiscale Air Quality (CMAQ) model (Byun and Schere, 2006), beginning with a detailed overview of the atmospheric chemistry and physics involved in their formulations. Additional information on this workshop is available at: http://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. 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 include the following:

a. Meteorology

- Urban canopy parameterization
- Modeling of clouds and precipitation, especially in the monsoon seasons
- Land-sea breezes in coastal cities
- Long-range transport (i.e. north-south flow that transports pollutants from source regions to the remote-rural areas).

b. Emissions

- Spatial and temporal emissions inventory from agricultural activities, both crop and animal (Aneja et al., 2011)
- Inventory of pollutants from key source sectors: Emissions of particulate matter (PM) from paved and unpaved roads. This is of particular concern in Indian cities. Current methods of estimating emissions from such sources are highly uncertain due to the lack of adequate inventories (Venkatram, 2001).
- Emission factors for various sources of black carbon (BC)**:** The studies of Venkataraman et al. (2005) and Bond et al. (2004) has shown strong evidence for the contributions of domestic biofuel combustion in India to the observed BC budget, identified as a significant component of the 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 black carbon budget.
- Chemical speciation, for soil-derived dust, and 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 such as compressed natural gas to diesel fuel.
- Development of top-down versus bottom-up emissions inventories to support air quality modeling studies, with case studies.

c. 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
- Integrated measurement-modeling studies to perform source attribution

d. Air quality modeling

- Lateral boundary conditions
- Chemical mechanisms to examine the very low observed ozone (Dickerson et al., 2002; Stehr et al., 2002)
- Interactions of meteorology and atmospheric chemistry (i.e., aerosols, radiation, clouds, and precipitation)

e. 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
- Future-year modeling including the interactions of climate and chemistry

f. Dispersion of pollutants within the urban canopy

3. Assessing the Future of Air Quality in the Tropics

Future scientific collaborations: As highlighted in previous sections, the primary goal was to bring together experts in the field of air quality and meteorological science from the U.S. and India to forge collaborations that will explore fundamental scientific challenges in this field, especially as it relates to urban- and regional- to global-scale processes. The Phase II expected outcome is a series of initiatives for scientific research and proposals for the same to be submitted to U.S. (e.g., NSF), and Indian funding agencies. The initiative will lay the groundwork for the subject areas and the order of priority of the challenges to be tackled via multiple research projects.

Contribution to enhancement/improvement of scientific, engineering, and/or educational activities: A key scientific contribution of this initiative will be an assessment of the state of the art in air quality management in India, and the development of 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. This summary assessment along with the set of recommendations are expected to be used to move forward to the next phase where concrete actions are taken by appropriate organizations/agencies that are involved in air quality management in India, both at the central and local/regional levels.

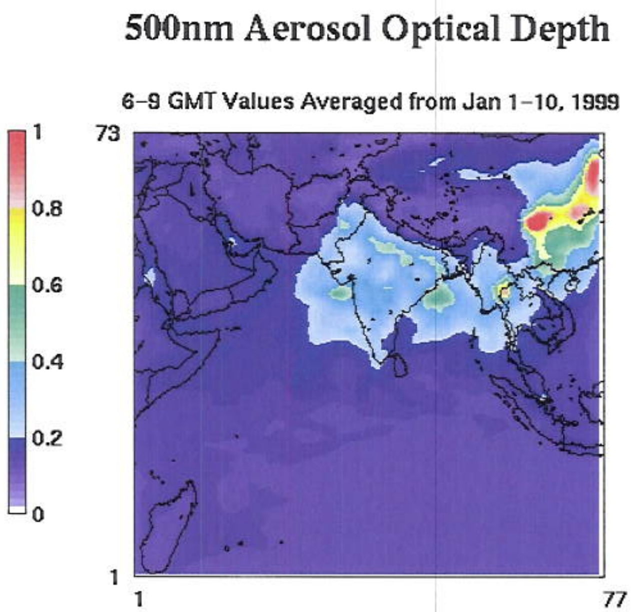
On the educational front, it is anticipated that a new generation of air quality and climate scientists drawn from various organizations and educational institutions in India will become proficient in Atmospheric Chemistry, Climate Science, and using the state-of-the-science models WRF, SMOKE and CMAQ to understand the various scientific issues related, respectively, to regional-to-urban-scale emissions, meteorology and air quality (http://www.epa.gov/amad) and assess the usefulness of the modeling system to Indian conditions. Further, the scientists from UNC on this team are senior staff at the U.S. EPA-funded Center for Community Modeling and Analysis System (CMAS) (cmascenter.org). CMAS is a means to promote the use of key modeling systems such as SMOKE and CMAQ and provide support and outreach to a growing world-wide user base (Rao, 2010). The bug-tracking facility on the CMAS website (http://bugz.unc.edu) as well as the CMAS listservs provide users tools to report problems on the use of these models, as well as query the system and the user community for existing help tickets and learn from solutions that have been offered in the past decade by the CMAS support staff. CMAS staff will continue to foster the expertise of this new generation of modelers in India using the existing infrastructure.

4. Linkages between Air Quality and Climate

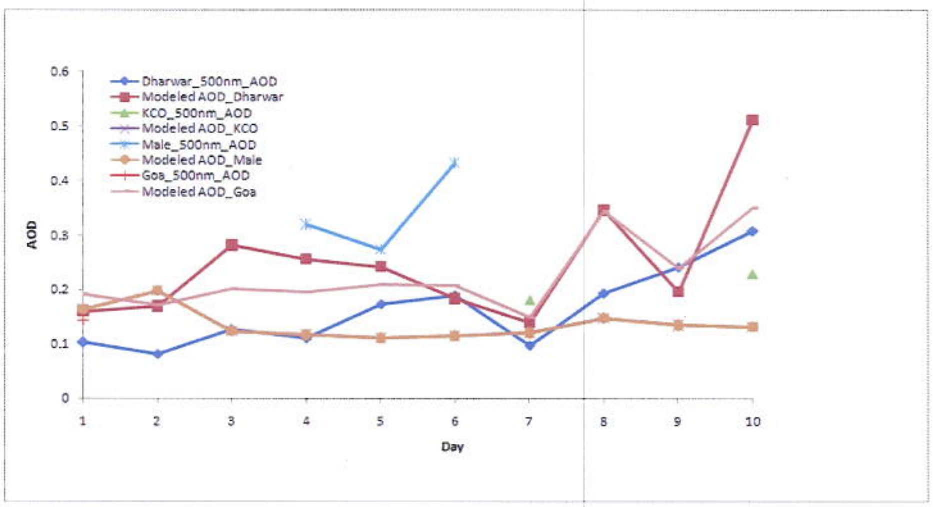
An emerging challenge in the science of air quality is its critical linkage to the climate change problem. This arises because certain atmospheric species have the ability to affect both air quality and climate. Changes in emissions of primary or precursor pollutants can result in increases or decreases in some of the climate-active species, e.g., BC and sulfate aerosol, which, in turn, represent a positive and negative forcing, respectively, on the climate system. Changes in surface emissions affect tropospheric chemistry, in turn affecting tropospheric ozone and methane which are climate-warming gases. Thus, reduction in methane a greenhouse gas that leads to a net increase in tropospheric ozone, is a potential "win-win-win" circumstance, with gains to be accrued in climate, air quality, and health outcomes (Horton et al., 2010). In contrast, changes in climate such as warming can act to enhance tropospheric ozone levels and thus exacerbate air quality degradation. Similarly, actions undertaken to reduce sulfur emissions from fossil fuel combustion to improve visibility and removing a respiratory health hazard in dense metropolitan areas has consequences for climate. In this case, however, this climate impact, unlike the methane/tropospheric ozone case mentioned above, may represent a "win-loss" situation because there is potential for rapid warming in the short term when the negative forcing of sulfate is removed (Horton et al., 2010). This near-term warming occurs because CO_2 and the other greenhouse gases have much longer lifetimes than the short-lived sulfate aerosols, and because their atmospheric concentrations are projected to continue to increase due to present levels of emissions. The Indian air quality issue and its links to climate are juxtaposed with corresponding challenges in the entire Asiatic region (Ramaswamy, 2009), and have relevance in the global dimension. Thus the key scientific considerations for air quality include a quantification of 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 is: 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 (e.g., heat waves, changes to monsoon patterns resulting in droughts and floods and the impacts on the food and water security in geographically similar parts of the world)?

Acknowledgment

We acknowledge support from the U.S. National Science Foundation (grant number OIES-1034759), U.S. Environmental Protection Agency, U.S. National Oceanic and Atmospheric Administration, and U.S. Department of Energy (grant number DE-sc0005901). We also acknowledge support from the following organizations in India: All India Council for Technical Education (AICTE), India Oil & Natural Gas Corporation Ltd. (ONGC), India Ministry of Earth Sciences (MoES), India Ministry of Environment & Forests (MoEF), Andhra Pradesh Council for Science and Technology (APCOST), Andhra Pradesh Pollution Control Board (APPCB), and Andhra Pradesh Department of Science & Technology [DST].



(a)



(b)

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. Modeled AODs at KCO and Male are indistinguishable due to the close proximity of these sites.

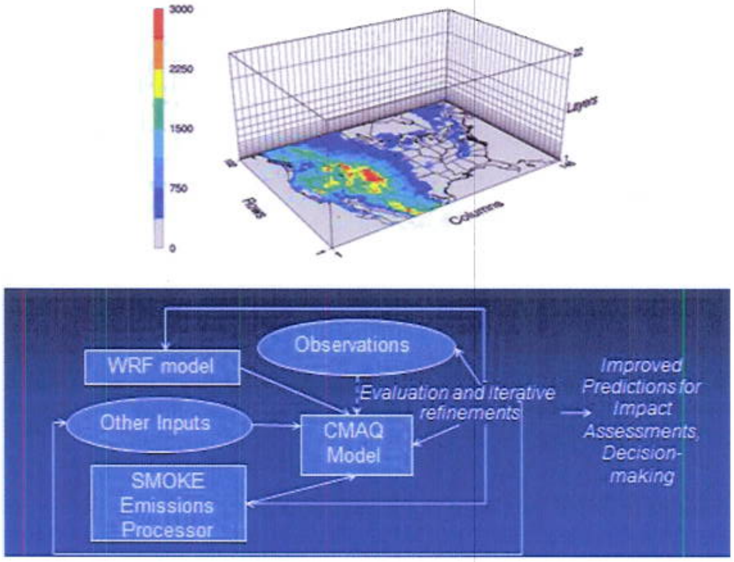


Figure 2. Flow diagram of the WRF-SMOKE-CMAQ modeling system distributed by the CMAS Center for research and regulatory applications. Also shown is an example modeling grid (vertical axis shows the height above surface in meters).

References

Airports Council International, 2011.

Aneja, V.P., A. Agarwal, P.A. Roelle, S. B. Phillips, Q. Tong, N. Watkins, and R. Yablonsky, Measurements and analysis of criteria pollutants in New Delhi, India, *Environment International, 27*, 35-42, 2001a.

Aneja, V.P., P. A. Roelle, G. C. Murray, J. Southerland, J. W. Erisman, D. Fowler, W. A. H. Asman, and N. Patni, "Atmospheric Nitrogen Compounds II: Emissions, Transport, Transformation, Deposition and Assessment", *Atmospheric Environment*, Vol. 35, pp. 1903-1911, 2001b.

Aneja, V.P., W.H. Schlesinger, and J.W. Erisman, "Farming pollution", *Nature Geoscience*, vol. 1, pp. 409-411, 2008.

Aneja, V.P., W.H. Schlesinger, and J.W. Erisman, "Effects of Agriculture upon the Air Quality and Climate: Research, Policy and Regulations", *Environmental Science and Technology,* vol. 43, pp. 4234-4240, 2009.

Aneja, V.P., W. Schlesinger, J.W. Erisman, S. Behera, M. Sharma and W. Battye, "Reactive Nitrogen Emissions from Crop and Livestock Farming in India", *Atmospheric Environment*, in press, 2011.

Bond, T.C., D.G. Streets, K.F. Yarber, S.M. Nelson, J.-H. Woo, and Z. Klimont, A Technology-Based Global Inventory of Black and Organic Carbon Emissions from Combustion, *J. Geophys. Res.*, *109*, D14203, doi:10.1029/2003JD003697, 2004.

Byun, Daewon and Kenneth L. Schere, Review of the Governing Equations, Computational Algorithms, and Other Components of the Models-3 Community Multiscale Air Quality (CMAQ) Modeling System, *Appl. Mech. Rev.* 59, 51, 2006.

de Laat, A. T. J., G. J. Roelofs, J. Lelieveld, R. J. Dickerson, and J. M. Lobert, Source analysis of carbon monoxide pollution during INDOEX 1999, *J. Geophys. Res., 106*(22), 28,481-28,496, 2000.

Dennis, R, Tyler Fox, Montse Fuentes, Alice Gilliland, Steven Hanna, Christian Hogrefe, John Irwin, S.Trivikrama. Rao, Richard Scheffe, Kenneth Schere, Douw Steyn, and Akula Venkatram, A Framework for evaluating regional-scale numerical photochemical modeling syastems, *Environ. Fluid Mechanics*, vol.10, pp. 471–489, doi: 10.1007/s10652-009-9163-2, 2010.

Dickerson, R. R., M. O. Andreae, T. Campos, O. L. Mayol-Bracero, C. Neusuess, and D. G. Streets, Analysis of black carbon and carbon monoxide observed over the Indian Ocean: implications for emissions and photochemistry, *J. Geophys. Res.*, *107*, 8017-8027, 2002.

Government of India, Ministry of Environment and Forests, *State of the Environment Report*, New Delhi, 2009.

Guazotti, S. A., K. R. Coffee, K. A. Prather, Continuous measurements of size-resolved particle chemistry during INDOEX-Intensive Field Phase 99, *J. Geophys. Res., 106*(D22), 28,607-28,627, 2001.

Habib G., C. Venkataraman, T.C. Bond, and J. J. Schauer, Chemical, microphysical and optical properties of primary particles from the combustion of biomass fuels, *Environ Sci Technol. 42*(23), 8829-34, 2008.

Hanna. A. F., K B. Yeatts, A. Xiu, Z. Zhu, R. L. Smith, N. N. Davis, K. D. Talgo, G. Arora, P. J. Robinson, Q. Meng, and J. P. Pinto, 2011, Associations between Ozone and Morbidity using the Spatial Synoptic Classification System, *Environmental Health,* **10**:49 (24 May 2011 http://www.ehjournal.net/content/10/1/40, 2011.

Horton, R., C. Rosenzweig, V. Ramaswamy, P. L. Kinney, R. Mathur, J. Pleim and V. Brahmananda Rao, Air Quality Modeling and Analysis, *Atmospheric Pollution Research 1*, xx-yy, 2010.

Houyoux, M. R., J. M. Vukovich, C. J. Coats Jr., N. J. M. Wheeler, and P. S. Kasibhatla (2000), Emission inventory development and processing for the Seasonal Model for Regional Air Quality (SMRAQ) project, *J. Geophys. Res.*, 105(D7), 9079–9090,

Kesarkar, Amit P., Mohit Dalvi, Akshara Kaginalkar, Ajay Ojha, Coupling of the Weather Research and Forecasting Model with AERMOD for pollutant dispersion modeling. A case study for PM10 dispersion over Pune, India, *Atmospheric Environment*, Volume 41, Issue 9, March 2007, Pages 1976-1988, ISSN 1352-2310, DOI: 10.1016/j.atmosenv.2006.10.042.

Levy, JI, M. Woody, BH Baek, U. Shankar and S. Arunachalam (2011) Current and Future Particulate Matter-related Mortality Risks from Aviation Emissions in the United States, *Risk Analysis*, Accepted, June 2011.

Mayol-Bracero, O. L., R. Gabriel, M. O. Andrae, T W. Kirchstetter, T. Novakov, J. Ogren, P. Sheridan, and D. G. Streets, Carbonaceous aerosols over the Indian Ocean during the Indian Ocean Experiment (INDOEX): chemical characterization, optical properties, and probable sources, *J. Geophys. Res., 107*(D19), 8030, doi:10.1029/2000JD000039, 2002.

Narain, U., "Policy Monitor: Urban Air Pollution in India", *Rev. Environ. Econ.Policy*, 2(2), 276-291, 2008.

Novakov, T., M.O. Andreae, R. Gabriel, T.W. Kirschstetter, O.L. Mayol-Bracero, and V. Ramanathan, Origin of carbonaceous aerosols over the tropical Indian Ocean: Biomass burning or fossil fuels?, *Geophys. Res. Lett., 27*, 4061-4064, 2000.

Ramanathan, V., and P. J. Crutzen, New Directions: Atmospheric brown ''clouds'', *Atmos. Environ., 37*, 4033, 2003.

Ramanathan V., P. J. Crutzen, J. Lelieveld, A. P. Mitra et al., Indian Ocean Experiment: An integrated analysis of the climate forcing and effects of the great Indo-Asian haze, *J. Geophys. Res., 106*(D22), 28,371-28,398, 2001.

Ramaswamy, V. Anthropogenic climate change in Asia: Key challenges, *EOS Transactions, American Geophysical Union*, 90, 49, 469-471.

Rao, S.T., Editorial - Special Issue: Air Quality Modeling and Analysis, *Atmospheric Pollution Research 1*, 195-195, 2010.

Reddy, M. S., O. Boucher, C. Venkataraman, S. Verma, J.-F. Léon, N. Bellouin, and M. Pham, General circulation model estimates of aerosol transport and radiative forcing during the Indian Ocean Experiment, *J. Geophys. Res., 109* , D16205, doi:10.1029/2004JD004557, 2004.

Reddy, M. S., and C. Venkataraman, Inventory of aerosol and sulphur dioxide emissions from India: I—Fossil fuel combustion, *Atmos. Environ.*, *36*, 677-697, 2002a.

Reddy, M. S., and C. Venkataraman, Inventory of aerosol and sulphur dioxide emission from India. Part II—biomass combustion, *Atmos. Environ.*, *36*, 699-712, 2002b.

Satheesh, S. K. and J. Srinivasan, Enhanced aerosol loading over Arabian Sea during the pre-monsoon season: Natural or anthropogenic? *Geophys. Res. Lett., 29*(18) 1874-1877, 2002.

Shankar, U., A. Xiu, D. Streets, J. M. Vukovich, M. S. Reddy, C. Venkataraman, R. Mathur, A. F. Hanna, F. S. Binkowski, and S. Arunachalam, Evaluation of a Coupled Meteorology-Chemistry Model Against INDOEX. In *Abstracts of the AAC-2005 Fourth Asian Aerosol Conference*, Mumbai, India, December 13-16, 2005.

Skamarock, W., J.B. Klemp, J. Dudhia, D.O. Gill, D.M. Barker, M.G. Duda, X-Y, Huang, W. Wang, J.G. Powers, 2008: A Description of the Advanced Research WRF Version 3. NCAR/TN-475+STR. http://www.mmm.ucar.edu/wrf/users/docs/arw_v3.pdf

Stehr, J. W., W. P. Ball, R .R. Dickerson, B.G. Doddridge, C.A. Piety, and J.E. Johnson, Latitudinal gradients in O_3 and CO during INDOEX 1999, *J. Geophys. Res.*, 107(D19), 8015, doi:10.1029/2001JD000446, 2002.

Tagaris, E., K. Manomaiphiboon, K.-J. Liao, L. R. Leung, J.-H. Woo, S. He, P. Amar, and A. G. Russell, Impacts of global climate change and emissions on regional ozone and fine particulate matter concentrations over the United States, *J. Geophys. Res.,* 112, D14312, doi:10.1029/2006JD008262, 2007.

Venkataraman, C., G. Habib, D. Kadamba, M.Shrivastava, J.-F. Leon, B. Crouzille, O. Boucher , and D. Streets, Emissions from Open Biomass Burning in India: Integrating the Inventory Approach with High-Resolution Moderate Resolution Imaging Spectroradiometer (MODIS) Active-Fire and Land Cover Data", *Global Biogeochemical Cycles, 20*, GB2013, doi:10.1029/2005GB002547, 2006.

Venkataraman, C., G. Habib, A. Eiguren-Fernandez, A. H. Miguel, and S. K. Friedlander, Residential biofuels in S. India: Carbonaceous aerosol emissions and climate impacts, *Science, 307*, 1454-1456, 2005.

West, J. J., A. M. Fiore, L. W. Horowitz, and D. L. Mauzerall, Global health benefits of mitigating ozone pollution with methane emission controls, *Proceedings of the National Academy of Sciences, 103*, 3988-3993, 2006.

Woody, M., B.H. Baek, Z. Adelman, M. Omary, Y.-F. Lam, J. West and S. Arunachalam, An Assessment of Aviation Contribution to Current and Future Fine Particulate Matter in the United States, *Atmos. Environ., 45 (20),* 3424-3433, DOI: 10.1016/j.atmosenv.2011.03.041, 2011.