Symposium Summary: Exporting and Importing Air Pollution, Regional and Global Transport

February 2002

MIT LFEE 2002-001 RP

Sponsored by the MIT Laboratory for Energy and the Environment
11-12 July 2001
Endicott House
Dedham, Massachusetts

Massachusetts Institute of Technology
Laboratory for Energy and the Environment
77 Massachusetts Avenue
Cambridge, MA 02139-4307

http://lfee.mit.edu/publications/
Publication No. LFEE 2002-001 RP

Exporting and Importing Air Pollution,
Regional and Global Transport.

MIT Laboratory for Energy and the Environment
July 11-12, 2001
Endicott House, Dedham, MA

Symposium Chair,
Robert Slott

Program Committee
Praveen Amar, NESCAUM
Maria Constantini, The Health Effects Institute
John Seinfeld, California Institute of Technology

Sponsors
American Chemistry Council,
Chevron,
California Air Resources Board,
The Health Effects Institute,
EPA,
EPA Center for Airborne Organics,
Exxon/Mobil,
MARAMA,
MIT Laboratory for Energy and the Environment
Pennsylvania Power & Light,
PGE National.
NESCAUM,
NACEC,
Toyota,
Volpe Research Center - DOT.

July 11, 2001

8:15 AM **Introduction**: Russell Dickerson, University of Maryland:
8:55 AM **Ozone Transport in the US**, Chair, Russell Dickerson
9:05 AM Ted Russell, Georgia Tech, *Ozone Transport*
9:35 AM Ken Schere, EPA, *North American Research Strategy for Tropospheric* Ozone *(NARSTO) Ozone and Particles Research Effort.*
10:05 AM ***Break***
10:25 AM Terry Keating, EPA, *Comparison of US and Europe Regional Ozone Policy.*
11:55 AM **Panel on Ozone Transport Assessment Group,(OTAG),** Alex Farrell, CMU
Mike Koerber, LADCO, *Dealing with Transport: (Midwestern) State Perspective*
Rich Poirot, Vermont Department of Environmental Protection, *Addressing Regional Air Pollution Transport: Lessons from OTAG*
11:45 AM ***Lunch***
1:00 PM **Particulate Transport in the US**: Chair, Praveen Amar, NESCAUM
1:15 PM John Watson, DRI, *Intra- and Inter-basin pollutant transport in Central California*
1:45 PM Bill Neff, NOAA, *What the NFRAC Study can tell us about PM Transport.*
2:25 PM Al Hansen, EPRI, *Inferring Transport of Air Pollutants*
2:55 PM ***Break***
3:15 PM Joe Paisie, EPA, *What should we learn from our experience with regional ozone control policy that we should apply to regional PM?*
3:45 PM **Health Effects Associated with Long Range Transport**: Chair, Maria Constantini, HEI
4:00 PM Tina Bahadori, American Chemistry Council, *Exposure*
4:40 PM Morton Lippman, NYU, *Epidemiology*,
5:10 PM Dan Krewski, University of Ottawa, *Re-Analysis of PM Studies*,

July 12, 2001

8:15 AM **Mexico/US Cross-Border Transport**: Chair, John Watson, Desert Research Institute
8:30 AM Bob Currey, UTEP, Paulette Middleton, Rand, and Carlos Rincon, Environmental Defense
9:50 AM ***Break***
10:10 AM David Allen, UT, TexAQS 2000
10:40 AM **US/Canada Cross-border Transport**, Chair: Paul Miller, NACEC
10:50 AM Jane Barton, Environment Canada
11:50 AM ***Lunch***
1:30 PM **Long Range Transport; Chair**, Glen Cass, Georgia Tech
1:40 PM Mario Molina, MIT, Impact On Air Quality Of Industrial Globalization And Long-Range Transport of Pollutants.
2:10 PM Terry Keating, EPA, Summary of June 2001 Conference On The Transport of Pollution From North America To Europe,

2:35 PM Greg Carmichael, U Iowa, Pollution from China,
3:05 PM Glen Cass, Long range PM transport from India,
3:35 PM ***Break***
3:55 PM **What are highest priority topics for a research agenda?**, Discussion Led by Mario Molina
5:00 PM Symposium Ends

Russell Dickerson, The University of Maryland, *Tracking Tropospheric Ozone with TOMS*, opened the first session of the symposium with a discussion of prior field experiments, which were undertaken to determine the mechanisms of transport and the amount of air pollution transported. Dickerson emphasized that even short-lived pollutants tend to be regional in extent and can undergo intercontinental transport when mixed into the free troposphere. He noted that intercontinental transport is expected to increase in the future with most of the emissions growth in the developing world. In order to gain a more comprehensive understanding of these transport processes, a combined approach of process-oriented field experiments, numerical models and satellite images must be applied.

Ted Russell, Georgia Tech, *Long Range Transport of Ozone, PM and their Precursors*, discussed modeling results in the eastern US, to complement the experimental results of Dickerson. Russell emphasized that the environment into which NO_x is emitted will greatly impact its Ozone Production Efficiency, and the time scales of these processes are important in understanding their ultimate impact. He noted that the emissions have a larger regional impact on atmospheric fine particles than on ozone levels. The downwind impact of power plant emissions is higher on sulfate levels as deposition rate decreases. Compared to ozone, sulfates therefore have a larger regional scale transport component. According to Russell, these results indicate, approximate transport scales on the order of hundreds of kilometers for ozone, and thousands of kilometers for sulfate. Finally, he suggested that the "direct sensitivity approach" developed by him and others is an appropriate method for evaluating the effect of uncertainty/variability of input parameters on the model predictions.

Ken Schere, EPA, *The North American Research Strategy for Tropospheric Ozone (NARSTO). Ozone Assessment and Long-range Transport*, said that NARSTO was started in 1995, as a response to a recommendation of the NRC for better coordination of research and transport on tropospheric ozone. However, the scope of NARSTO has expanded to include ambient particulate matter research and, more generally, research on tropospheric air pollution. Observational evidence seen in recent North American and European studies indicates that transport of O_3 and its precursors can take place over distances exceeding 300-500 km under certain meteorological conditions. According to the NARSTO assessment, transport at the surface and aloft is a common feature in multi-day pollution episodes. The assessment included documentation of trans-boundary transport, highlighting several examples including southeast Canada–northeast US and US-Mexico border areas. Specifically, 50-60% of measured ozone levels in the greater Toronto area are attributed to contribution of regional transport from southeast Michigan. Schere pointed out that local controls by themselves were not sufficient due to international trans-boundary issues. Recognizing the important role long range transport of ozone and its precursors (especially oxides of nitrogen) plays in elevated ozone levels across the eastern US, OTAG (Ozone Transport Assessment Group was formed in 1995 and consisting of stakeholders from 37 eastern states and federal government, private sector, and academic community). OTAG agreed in 1997 on a set of regional control measures. These regional strategies later on became the basis for EPA's " Transport SIP call" measures to lower ozone levels across the eastern US. In addition to policy responses within the US, there are also joint commissions between the US and Canada and the US and Mexico, established to address issues related to the transport of air pollution across national boundaries.

Terry Keating, EPA, *Comparison of US and Europe Regional Ozone Policy*, discussed the issues of problem framing and model formulation by comparing the historic US and European approaches to the regional tropospheric ozone problem. The US started addressing pollution first on an urban scale, and only later attempted to solve pollution problems on a more regional scale. On the other hand, the Europeans started out dealing with issues of acid rain, and thus were framing the problem on a regional scale right from the beginning. Furthermore, in the US, policymakers took a human health perspective, while the European perspective reflected more of an ecological viewpoint from dealing with issues of acid deposition. With regard to the European Union Regulatory Framework, Keating noted that the underlying philosophy for air quality management was to move away from standards and toward setting long-term air quality objectives based on both human health and vegetation.

Panel on OTAG Chair, Alex Farrell, Carnegie Mellon University. Observing the discussion on Capitol Hill, Farrell noted that there are several upcoming challenges for air pollution regulation, not the least of

which involves the debate over pollutant standards, and whether they should be single or multi-pollutant. Another emerging issue relates to mercury transport, which behaves quite differently from the other pollutants that have been discussed thus far. There are also important longer-term issues such as new electrical generation technologies, including distributed generation technologies, and the possibility of carbon dioxide control policies leading to carbon sequestration technologies. These sequestration technologies could, however, involve the introduction of new trace chemicals into the atmosphere.

Rich Poirot, Vermont Department of Environmental Protection, *Addressing Regional Air Pollution Transport: Lessons from OTAG*. OTAG succeeded in attracting hard working and clever participants, in part because it was addressing an interesting scientific problem, but also because it provided an opportunity to affect public policy in a tangible way. Additionally, there was an implied "hammer," or consequence to a failure by OTAG, since there was a real threat of the process being thrown into the courts if this group failed. There were frequent interactions open between scientists and policymakers , which helped to bring about consensus. The OTAG geographic area of interest, the domain, was exactly the right size for the scale of regional ozone transport in the east. Almost all the ozone in the domain arose from within the domain. At the corners of the domain, median ozone reaches tropospheric background levels, and meteorological flows from any direction outside the domain typically results in below-average ozone within the domain. Importantly, for the first time there was both formal recognition and funding for data analysis as a complementary activity to the traditional photochemical grid modeling approach. Considering the possibility of applying a similar multi-jurisdictional group process to address transport of $PM_{2.5}$ and/or regional haze, he emphasized the strong differences between the East and West, which present different issues for both pollutants and transport scales. There are five regional planning organizations (RPOs) for addressing the issue of regional haze (regional visibility degradation). However, according to Poirot, the sizing of the haze RPOs is geographically backwards, with a single large region covering the entire West, and four smaller regions dividing the East.

Michael Koerber, Lake Michigan Air Directors Consortium (LADCO), *Dealing with Transport: (Midwestern) State Perspective*, The Lake Michigan Ozone Study (LMOS) was a state-led effort involving Wisconsin, Illinois, Indiana, Michigan and the USEPA. These states needed a regional regulatory approach to deal with ozone transport in the Lake Michigan region. The LMOS was designed as a regulatory project with the objectives of: 1) developing a data base and planning tools (models), and 2) applying these models to develop a regional attainment strategy. According to Koerber, OTAG was a technical success, as it updated the science and understanding of ozone transport. Politically, however, OTAG had some shortcomings with many vague policy strategies resulting from the process according to Koerber. These shortcomings can be seen in the number of states named in Section 126 and Section 110 petitions. The political outcome was incomplete, highlighting one of the future challenges of these assessments – the need to do a stronger job on the political side. The regulatory approach, as suggested by Koerber, should be incremental, moving away from the Clean Air Act framework of either attainment or non-attainment toward establishing and tracking goals. There is also a need for greater flexibility. While the "one size fits all" approach may be more efficient administratively, this is not the most effective approach for reducing emissions.

Particulate Transport in the US, Chair, Praveen Amar, NESCAUM. Amar opened the session on particulate transport by noting that the science of long-range transport of particulate matter was rapidly emerging. The new federal ambient standards on PM2.5 (long-term, annual and short-term, 24-hr) will require various regions in the US to design and implement control strategies to achieve these standards in the 2005-2010 time frame. He also noted that there were some important scientific issues that were common between ozone and PM2.5, but also some that were not, and both of these need to be taken into account in designing optimum strategies to reduce both the ozone and particulate matter concentrations. The afternoon session included three presentations on field studies, and one on policy issues related to particulate transport in the US.

John Watson, Desert Research Institute, *Intra- and Inter-basin pollutant transport in Central California.* Watson outlined a wintertime conceptual model for the San Joaquin Valley that indicated a region-wide nitrate control effort is needed to reduce PM levels. Horizontal transport and vertical mixing in air are related, pollution transport cannot be understood without understanding vertical mixing. Pollutants are

separated from the surface for nearly two-thirds of every day, minimizing deposition and fostering long reaction times. As a result, pollutants can move farther from their source, as much as 50 to 300 km during a single day, and many episodes last several days. There is ample opportunity for emissions in one part of the San Joaquin Valley to affect concentrations in other parts of the valley. Watson said many lessons on managing field studies were learned. First, sustained, long-term efforts are needed to understand regional air quality problems with pollutant transport from one area to another. Second, upper air and surface meteorological measurements must accompany air quality measurements. Third, it is necessary to formulate a conceptual model using the available information and then design a network to test that model. Fourth, resources should be better divided among all study elements, by budgeting for data validation and interpretation up front. In other words, researchers need to be funded to analyze data as well as to collect it. Finally, a balance between high, medium, and low technology monitoring is needed to permit broad spatial, and temporal coverage.

William Neff, NOAA/OAR, *What we have learned from The Northern Front Range Air Quality Study (NFRAQS) about winter fine particle transport in complex terrain*. The objective of this study was the apportionment of fine-particle mass to sources for the northern Front Range of Colorado, with its highly complex terrain and a combination of, elevated and ground-based urban and rural sources. Transport, in general, is away from the Front Range. While there is an eastward drift, there are also some periods of circulation from the east. Upslope flows and strong inversions are also a critical piece of the fine-particle puzzle. For example, looking at 7-hour samples, one observes that after about three hours, there is some transport of secondary particles back from the east. High levels of ammonium sulfate and nitrate require prolonged northeasterly moist airflow into Denver from rural areas. A broader question is whether Denver is unique, or whether the upslope-recirculation flows seen in the Front Range occur in other places with similar terrain. Looking at other regions, such as the northeast corridor in the US, Munich, Germany, and Calgary, Canada, these flows are rather common over this type of terrain. Because of terrain following flows, such as those found in Denver, the contrast in pollution between urban and rural areas is not as great as might be expected. For example, rural areas such as those around Evans and Masters, Colorado show PM concentrations on the same order as those found in Denver. Furthermore, small changes in elevation can make a significant difference in concentrations. For example, in Brighton, which sits slightly higher in elevation, one can see sharp changes in fine particle concentrations over short time periods. According to Neff, this is due to the "sloshing" of fine-particle laden cold air from the South Platte River low-lands up onto the higher terrain of Brighton. Neff concluded by emphasizing that weather and climate play critical roles in the nature of pollution episodes and the relative concentrations of its constituents and their transport. Therefore, there is a need for long term and continuous observations of air chemistry and meteorology, in order to understand the effects of short- and long-term climate variability.

Alan Hansen, EPRI, *Issues Arising Regarding Transport and Transformation of Atmospheric Emissions from Electricity Generating Stations*. Hansen noted that one of EPRI's objectives is to characterize the role of power plants in a broader context, by quantifying the absolute and relative contributions of power plant emissions to air pollution and its impacts. The research emphasis is on realistic reactive plume modeling, with Models-3 serving as the developmental platform. EPA is planning to rely on this model. Some of the enhancements made to Models-3 include plume-in-grid modeling and comprehensive treatment of particulate matter chemistry and dynamics. Hansen believes these enhancements will enable better characterization of particulate matter composition and its behavior or local and regional scales.

Joe Paisie, EPA, *What should we learn from our experience with regional ozone control policy that we should apply to regional PM?* The regional PM strategy the EPA plans to pursue has four core objectives: (1) encourage states to work together, (2) develop an economic incentive approach, (3) support coordination between states, and (4) fully implement the federal acid rain program to reduce annual SO2 emissions by about 10 million tons by 2010. This strategy is one of "start big and go small." In order to support regional strategies, five regional planning organizations (RPOs) were formed. These RPOs were established by the US EPA after consultation with states environmental commissioners. As a result, the RPOs were organized as follows:

1. WRAP includes the western US ?from California to New Mexico, Colorado and the Dakotas ?and was a follow on to the Grand Canyon visibility study. WRAP came forward with agreement on improving visibility in the West. EPA has taken their reductions and put them into the regional haze plan.

2. CENRAP includes the agricultural states and Texas.
3. Midwest RPO includes Ohio, Indiana, Illinois, Michigan and Minnesota.
4. Northeast RPO extends from the District of Columbia and Maryland to Maine.
5. VISTAS covers the entire southeastern US.

The first year priorities for the four new RPOs (includes all but WRAP) was to "get organized" within their new organizations and with respect to their state-tribal relationships, and "get smarter" through the establishment of technical working groups and actually begin technical assessments for their region. The goals of the next 6 to 24 months were to (1) continue building relationships, including those with federal land managers, environmental groups, and industry, (2) define the technical problems and identify available tools, and (3) plan near- and long-term technical work through the RPOs. In conclusion, Paisie touched upon four main topics for consideration with regard to regional PM control strategies: (1) public awareness, (2) institutional issues, (3) control program issues, and (4) legal considerations. According to Paisie, there is growing public awareness of PM. The issue of visibility in national parks, for example, has helped in raising support for control measures. The difference in urban visibility can also be dramatic, which could be an advantage from the policy standpoint, since the public actually sees the benefit. Many institutional issues remain to be resolved with respect to how the federal-state system works on addressing an interstate and a regional problem. Control program issues also remain. One of the accomplishments of the acid rain program was that it required a regional solution to a truly regional problem, and by using market-based "cap and trade" approach, substantially brought down the cost of implementation. According to Paise, the regional strategies such as "cap and trade" are less effective in addressing those environmental problems that are more local in nature. Finally, there are important legal considerations in moving forward on regional control measures. This is linked to the Clean Air Act, which is clearly structured from a bottom-up standpoint. Because of this, if an area measures high concentrations, that area is then responsible for reductions. It is difficult to make progress, however, if the pollutants came from somewhere else. As noted by Paisie, any attempts to change this legal structure will have to come at the initiative of Congress.

Health Effects Associated with Long Range Transport Chair, Maria Costantini, Health Effects Institute

This session discussed efforts to determine the contribution of long-range air pollution transport to exposure and health effects. With regard to exposures the main question is how we determine how different sources (regional and local) contribute to personal exposure. One approach to understanding the health effects of pollution from different sources is by population studies that compare health effects in people who live in areas with different pollutant mixes. Data analyses should account for various components of the air pollution mix and for spatial correlations. However, in most of these studies, exposure is determined from ambient concentrations and may not reflect the true exposure mix for individuals in the study. Another approach to study health effects involves toxicological studies. For measuring the impact of particulate matter (PM) such studies offer the advantage that they can use PM from specific sources or concentrated ambient particles (CAP). The latter type of exposure delivers a varying mix of locally generated and transported PM to the animal and can be a useful tool for understanding the health impacts of long-range transport. One example of an experimental study using CAP is a study conducted by Dr. John Godleski (Harvard School of Public Health) to determine cardiopulmonary effects in dogs exposed to CAP for three days. The study also sought to determine whether certain components of PM, such as a metal, or different weather conditions, might be responsible for the cardiac effects observed. The results revealed large variations in ambient PM and CAP composition on different days, suggesting that the contribution of PM from different sources varies from day to day. The investigators found a trend associating metal components (primarily nickel) and cardiopulmonary responses. The investigators further analyzed the potential role of transported components by relating effects to the trajectory of the air mass on a given day. On the majority of the days, the direction of the air mass was from the northwest and north-northwest, on the other days it was from west and south-southwest. When analyzing the cardiac changes according to these trajectories, different patterns appeared, suggesting that particles of different origins have different effects on cardiac parameters. (These findings are presented in the Health Effects Institute Research Report No. 91.) Although this study needs to be confirmed by studies with more animals and more exposure days, it represents a novel approach to studying the contribution of local and more remote sources of particles.

Tina Bahadori, American Chemistry Council, *Exposure Implications of Regional and Global Transport of Air Pollution*. The impact of regional and global transport on human health is a complex process of

multiple pathways and multiple pollutants. Researchers looking at health effects already struggle with assessing the different impacts of indoor versus outdoor exposures and the importance of stationary versus mobile sources. Differentiating between local versus regional sources, and now even global sources, adds an extra layer of complexity to the already difficult process of determining exposures. One core question is whether regional and global sources lead to an escalation of background levels or the introduction of new pollutants or new pollutant characteristics. In the US, 95% of an individual's time is spent in indoor environments. While this is dependent to some extent on the building and housing characteristics in which people spend most (if not all) of their time, it is also true that outdoor sources are typically the largest contributor to indoor levels. Turning to the regional aspect of exposures, analysis of outdoor PM data from historical studies show regional characteristics. In the urban northeast, on average, 75-95% of PM_{10} is composed of $PM_{2.5}$ with most of the variability in $PM_{2.5}$ driven by the variability in sulfate concentrations. In the urban west, about half of PM_{10} is composed of $PM_{2.5}$, with the variability driven by changes in coarse PM concentrations. While one can speak more definitively about sulfates, since most historical studies focused on measurement and analysis of sulfates, much less is know about the other components of fine PM such as organics, nitrates, and metals. This is due both to a lack of measurement methods, and a more complex array of sources. While these discussions focus on ambient concentrations, she noted that even less is know about the composition of personal $PM_{2.5.}$ New data from studies such as the PM Centers, Supersites, and panel studies of exposure and health, will help to characterize the concentration and composition of air pollution for major urban centers. However, this information is only going to trickle out over the next five years. There is also work on developing new methods for source apportionment of personal exposures, differentiating between mobile or stationary, and local or regional sources.

Morton Lippmann, New York University School of Medicine, *Epidemiology of Air Pollution.* Speaking first to the effects of ozone, studies of the impacts of ozone exposures have shown that individual responses vary, and the effects of ozone are more acute than chronic. Ozone works as a deep lung irritant, with the effect building up over multiple hours. Therefore, it is the integral daily exposure that matters more than peak exposures. For ozone exposures, several NYU field studies and various controlled human exposure studies in laboratories revealed that, although there is a group mean response, responses vary considerably among individuals.

Turning to PM, Lippmann then described a study of the concentration of fine PM in Buffalo and Rochester. Inter-comparisons of sulfate and daily acid particulate matter concentrations for 1990, showed these measures of fine PM were uniformly distributed for Buffalo and Rochester. Since there are many kinds of particles in ambient air PM, an important question from the health effects standpoint is how PM is measured, whether by number, surface, volume, as well as the size of the particles that are sampled. The distribution plots over particle diameter are quite different if looking at plots according number, surface or volume of particles. For example, the frequency plot of volume is a bimodal distribution, with fine particles between 0.01 and 2 µm, and coarse particles at > 2 µm, while the distributions of surface and number are generally uni-modal, with ultra-fine dominating the number concentration and fine particles dominating the surface concentration. The composition of ambient particulate matter is important. There are different kinds of chemicals in fine and coarse particles. Fine mode particles are acidic and appear dark because of diesel soot and secondary organics formed by photochemistry in the atmosphere. Coarse mode particles, by contrast, are basic and lighter in color. The fine component of PM has been found to be consistently correlated with mortality, but what remains less certain is, within the fine particles, what components are important. The effects estimates for PM_{10} and hospital admissions, emergency rooms visits, or physicians office visits show that respiratory and cardiovascular admissions increase with increasing PM_{10} levels. Using a reconstructed excess risk percentage, there is small, but statistically significant, excess of acute cardiovascular hospital admissions with increases in PM concentrations of 50 $\mu g/m^3$. Evidence is emerging that due to the variety of components of ambient air PM – strong acid (H^+), ultra-fine particles, soluble transition metals and peroxides – some particles are worse than others are. For example, close proximity to roadways seems to be a relevant variable, indicating that transport on a short scale for freshly formed (ultra-fine) PM may be important in terms of risk assessment.

Daniel Krewski, University of Ottawa, *Re-Analysis of the Harvard Six-Cities Study and the American Cancer Society Study of Air Pollution and Mortality.* The re-analysis was a highly iterative process with two main phases. The data quality audit (Phase I) involved verification of the integrity of the original data.

The use of alternative risk models (Phase II) meant starting *carte blanche* to try alternative analytical techniques using the original data. The Harvard Six-Cities Study was conducted over a period of 20 years in six cities with a gradient of industrial SO_2 and TSP levels. Between 1974-77, 8,000 adult subjects were recruited, and were subsequently contacted at three, six and twelve years. Mortality follow-up was done through 1989, by which time a total of 1,400 deaths were registered. Looking at the original results, the Harvard Six-Cities Study, found an increased risk of 26% for all causes of death, and an increased risk of 37% for cardiopulmonary and lung cancer related deaths. Turning to the American Cancer Society (ACS) Study, this study defined a cohort of 1.2 million adults in 1982, using air pollution data from that year as an index of exposure for the entire time period. Mortality follow-up went up to 1989. There were two subsets in the original ACS Study, one with 550,000 people in 151 cities with sulfate particle measurements, and a second with 300,000 people in 50 cities with fine particle measurements. While in general the results were similar to those found in the Harvard Six-Cities Study, one interesting finding was with the relative risks for lung cancer with the sulfate group. Rates of pulmonary disease were statistically elevated with sulfate, with a relative risk of 1.36, which was not found in the Harvard study. Krewski then highlighted some of the key findings of the HEI re-analysis of these two studies.

(1) Phase I of the re-analysis generally confirmed the results of obtained by the original investigators of both the Harvard Six-Cities Study and the ACS Study.
(2) In Phase II, the results were found to be robust to alternative analytical methods. The Re-analysis team still found excess mortality for sulfates and fine particles even after incorporating spatial autocorrelation in the ACS data.
(3) In both studies, a clear modifying effect of education was found after adjusting for ecologic covariates.
(4) Among the gaseous co-pollutants considered in the ACS Study, only sulfur dioxide appeared to be associated with mortality.

Krewski emphasized that, collectively, these results suggest that mortality may be related to more than one component of the complex mixture of urban air pollutants. In terms of future work, there will be further follow-up of the ACS cohort. He will also be working on more refined spatial analytic methods, with much of the challenge in finding the right geographic unit. In addition, a group of subjects with complete residence patterns has been identified, therefore, allowing one to identify time-dependent critical exposure windows. Finally, in the future, a quality-adjusted life-expectancy measure will be used to assess the population health impact.

Jon Levy, Harvard School of Public Health, *Atmospheric Transport: A Risk Assessment Perspective.* Levy described some preliminary findings from power plant case studies being conducted at the Harvard School of Public Health, which investigated the magnitude and distribution of health benefits from emissions control of grandfathered power plants. To date, two studies have been completed, one in Massachusetts and one in Illinois. The key finding from the Massachusetts study was that emission reductions from two power plants would result in an annual average $PM_{2.5}$ concentration reduction as great as 0.2 $\mu g/m^3$. While this is a relatively small contributor to the total burden of ambient $PM_{2.5}$, Levy commented that it does not necessarily imply that controls are unnecessary; one must compare the costs and benefits of controls. Another important finding that came from this research was related to the spatial distribution of risk. How one thinks about the spatial patterns depends largely on whether one looks at individual risk or aggregate risk. For example, individual risk peaked close to the power plants, with risk from the plants 3-4 times greater for people living within 50 km of the power plants when compared with people living beyond 50 km to the end of the modeling domain. On the other hand, when considering aggregate risk, only a small fraction (approximately 10-30%) occurs within 50 km, because of the importance of long range transport for particulate matter. According to Levy, the total benefit of PM reductions was about 80 fewer deaths per year in a population of 33 million. The research on power plants could have implications for emissions trading, but it depends on whether one takes a state, local or national perspective in assessing risk. This study was done from the state perspective, and decision-makers in the state might be concerned about maximizing the benefits for the residents of their state. However, looking even more locally, on-site emissions reductions would be more strongly desired since it would significantly alter the benefits for the local populations living near the power plant. Because the distribution of risk depends on the results from atmospheric models, it is important to assess how much uncertainty could exist in the transport modeling from the perspective of health benefits assessment, and especially when policy decisions could be influenced by this uncertainty.

Mexico/US Cross-Border Transport Chair, John Watson, Desert Research Institute. Watson noted that many Mexican border cities are relatively large population clusters, meaning that cross-border transport will become increasingly important as emissions from these clusters grow. The standard viewpoint is that transport "always comes from the other guy," when in reality, pollution travels both ways. Looking at PM_{10} fluxes at Calexico/Mexicali there are both important southerly and northerly flows. While we can do blame matrices, these border communities really transcend the borders, both in terms of pollution and people.

Bob Currey, UTEP, *Air Pollution Transport in the Paso del Norte Region.* The Paso del Norte region, "Pass of the North," encompasses communities on both sides of the Rio Grande River. While it straddles two nations, three states, and three municipalities, in actuality the region is one community of 2.2 million people. The majority of this population, 1.5 million people, reside in Ciudad Juárez, with 700,000 in El Paso and relatively few in Doña Ana County. The Paso del Norte region will continue to experience rapid population growth as well as rapid industrial growth. In part, this demographic trend is inherent in the age of the population, as half of the people in Ciudad Juárez and one third of the people in El Paso county are under 18 years old. Economic conditions are not good even on the US side of the border. The impacts of an impoverished economy on air quality are numerous, ranging from poor municipal budgets, which leave many air quality and enforcement functions under-funded, to a proliferation of old cars. Geographically speaking, the region is also disadvantaged. This is a high mountain desert prone to many inversions. Looking at a topographic map of the region, one can see how the surrounding mountains lead to a lot of drainage from the high ground, with El Paso essentially in the "bottom of the bucket" with respect to these air mass flows. On the other hand, this is an isolated region from the perspective of long-range transport. Both an ozone study using aerial observations and PM/dust speciation showed little long-range transport coming into the valley. As stated by Currey, "we are in a world of our own."

El Paso has been in violation of three of the six NAAQS pollutants – ozone, PM_{10}, and CO – and faces further problems of regional haze and reduced visibility. For ozone, the VOC contribution of Ciudad Juárez is actually double that of El Paso. For this reason, those on the US side are considering the idea of financing vapor recovery systems on the other side of the border in order to capture these VOC emissions. This first requires exploring the legal changes needed to make cross-border emissions trading possible. Ciudad Juárez also leads in emissions of CO. However, El Paso had higher measured numbers for NO_x. In Ciudad Juárez a significant portion of PM emissions is related to unpaved roads and uncontrolled burning of waste. Also, the contributions of the brick kiln micro-industry are uncharacterized and unquantified, and therefore can not be said to be insignificant.

Carlos Rincón, Environmental Defense, *Mexico/US Cross-border Transport.* Rincón described efforts at multi-jurisdictional cooperation on problems ranging from air quality measurements and monitoring to specific programs and policies for mitigation. In the Paso del Norte, people have been learning how the air basin can be managed as one metropolitan area, and how to expand individual projects in order to generate even greater benefits from these projects. Joint Advisory Committees (JAC) were created for the development of the strategic plan and the sharing of information in support of air quality management for the shared air basin. In addition to policymakers, the JAC also include a diverse set of stakeholders and reflected strong levels of community input. All of the meetings of the JAC are open to the public. Thirteen resolutions were passed through consensus by the JAC and there are currently 26 projects under the basin-wide air quality management plan. However, according to Rincón, prioritization of these actions is now needed.

Within the Paso del Norte JAC for Air Quality, private vehicles were recognized to be the major source of emissions in the air basin, primarily for CO, but also for ozone and PM. The JAC also recognized that efforts at emissions reduction should not focus narrowly on combustion and fuel use, but also look at possibilities for transportation demand management and shifting to public transportation. This region is one of the world's major border crossings, linking Mexico and the US. Unfortunately, local vehicles, which are generally low-efficiency and with high-emissions, also have long waits (on the order of an hour) at border crossings, and during this waiting time these vehicles can produce very high levels of emissions. Another problem with the poor emissions performance of the private auto fleet relates to the importation of older, high emitting vehicles from the US into the Mexico border region, highlighting the need for better

enforcement of the importation rules for private vehicles. One other transportation-related pollutant source issue, poor infrastructure quality on the Mexican side of the border, illustrates the need for cross-border cooperation to address differences between Ciudad Juárez and El Paso. A large number of the roads in Ciudad Juárez are unpaved, which, when combined with increasing traffic, contributes significantly to rising concentrations of PM. In recent years, the Ciudad Juárez has seen annual population growth rates of greater than ten percent, making efforts to keep up with the supply of infrastructure and services a difficult task. Most of the unpaved roads in Ciudad Juárez are heavily traveled. In contrast, even alleys are being paved in El Paso. This disparity in the quality of the infrastructure between Ciudad Juárez and El Paso points to emissions reduction opportunities that are basin wide.

Paulette Middleton, RAND, *The Pollution-Policy Boundary Challenge: US/Mexico Example.* The pollution-policy boundary challenge arises from the fact that pollution is "unbounded." This leads to policy challenges on the local scale, as seen in border cities. For example, looking at US-Mexico pollution issues, border health is a major and growing concern on both sides of the border, with a growing need for detailed assessment. According to Middleton, the key needs for understanding these boundary challenges and carrying out effective policy development lies primarily in improved characterization of emissions, concentrations and related impacts, as well as increased collaboration among scientists and policy makers.

David Allen, The University of Texas at Austin, *Regional Transport of Ozone (and Fine Particulate Matter) within Texas.* In addition to three metropolitan areas in Texas – Houston, Beaumont/Port Arthur, Dallas/Fort Worth – that now violate the current 1-hour ozone standard, five other Texas areas are considered to be near non-attainment under the new 8-hour ozone standard. The air quality management plans call for significant reductions in emissions of nitrogen oxides, in order to bring air quality back into attainment. NOx controls are needed since the eastern half of Texas is heavily forested and about 80% of total VOC emissions in this region are from vegetation (both natural and agricultural). Even in the more urbanized eastern Texas counties, biogenic emissions of VOC play an important role, making it difficult to achieve major reductions in VOC. For example, biogenic emissions contribute 40% of total VOC emissions in Houston (Harris County).

Allen described the technical approach that was applied to evaluate regional transport in eastern Texas. Historical ozone episodes, where spatially and temporally resolved measured emissions data were available, were simulated with a photochemical model to obtain model parameters that correlated with the data. These parameters could be used in modeled sensitivity studies to evaluate regional transport. The sensitivity study methodology eliminated or "zeroed-out" anthropogenic emissions of NO_x, VOC, and CO from a region of interest (e.g., the city of Austin), and performing photochemical modeling to estimate that city's air quality when the region was not producing any of its own man-made emissions. After completing this type of analysis for each area, the conclusion was that every area impacts itself as well as at least one other near non-attainment or non-attainment area in Eastern Texas. The amount of the impact varies for different episodes because of differences in the prevailing meteorology. In other words, in eastern Texas, everybody is downwind of somebody else sometime. This evidence of inter-city ozone transport suggests that the state of Texas should continue pursuing a regional approach to air quality management.

Point source emissions of NO_x from large industrial facilities have contributed substantially to the regional ozone problem, but since the point sources have a wide range of ozone productivity efficiency (OPE), equal NO_x emission reductions at different point sources do not lead to equal reductions of ozone. Analysis showed that there were two types of facilities, high impact and low impact facilities. In terms of the transport distances for elevated point sources in Texas, distances over which 50% of the ozone impacts are observed can range from 150 up to 300 km from the point source. High impact facilities, which tend to be in rural areas with high biogenic hydrocarbon emissions and no other NO_x sources, have their major impact locally. On the other hand, low impact facilities (even if one takes into account the effect of local "disbenefits" or negative impacts) tend to generate ozone over larger distances. These results highlight the need to establish a clear framework for NO_x trading evaluation. Allen described how a modeling tool, CAMx, was used to generate an ozone productivity database and to develop quantitative ozone impact indices. Using the model as a NO_x trading tool, one could do simulations to see which facilities generate impact in which areas, and then to determine whether certain trading options would create a benefit or not. By applying optimization strategies and Monte Carlo simulation to case studies, the model could identify

"best" and "worst" case trading scenarios, quantify the likelihood of both "good" and "bad" trades and variability due to meteorological conditions, and evaluate "real-world" trading constraints. The distribution curve for trading benefits shows that extreme maximum and minimum benefit trade are highly unlikely, and that the impact index does not greatly impact the uncertainty distribution. This uncertainty analysis does suggest that one might want to place some restrictions on the trading benefits uncertainty, an issue which is discussed in a forthcoming article in the journal *Environmental Science and Technology*.

US/Canada Cross-border Transport Chair: Paul Miller, North American Commission for Environmental Cooperation (NACEC)

Miller gave some background regarding the NACEC, which could be characterized as the "NAFTA environmental commission." Some of the functions of NACEC include promoting information exchange and trying to anticipate potential trade constraints for environmental policies on all sides of the borders.

Jane Barton, Environment Canada, *Canada-US Cross-Border Transport*. The story of the Ozone Annex between the US and Canada is important as a cross-border pollution theme because it represents the first real use of "joint" analysis in North America to develop a policy-legal result. Barton's presentation outlined the ozone negotiations, moving from the idea of cross-border ozone pollution to the agreement and described how Canada seized the opportunity to change its air quality policy. The process with ozone was different from what occurred earlier with acid rain negotiations. With the ozone issue, joint analysis was used for the first time to (1) analyze and describe the transboundary issue and (2) define the legal commitments. Joint analysis will also provide the foundation to assess progress.

In Canada, the critical level for ozone, or Canada-wide Standard (CWS), is a health-driven ozone standard that is an intergovernmental agreement among federal and provincial Canadian governments. This is in contrast to a federally mandated standard such as the NAAQS in the US. The CWS for ozone is an 8-hour average of 65 ppb by 2010, which is slightly below the US' current 80 ppb 8-hour average. Exceedances of the 65 ppb ozone standard were occurring in areas with very low populations. Data from 1994-1996 suggested long-range transport from the US. Looking at the relative contribution from long-range transport, in Eastern Canada, cities such as London and Saint John showed a higher percentage of NO_x contributions coming from sources in the US than from Canada.

There were several factors that converged to create an opportunity for action: (1) the prior existence of both multilateral legal and bilateral cooperative mechanisms, (2) the OTAG Regional Transport NO_x SIP, and (3) the desire to push action before the end of the Clinton Administration due to uncertainty from administrative changeovers. A map of transport vectors for ozone in the Northeast US highlights the magnitude of long-range transport from the US to Eastern Canada. Forecasts of emissions under the implementation of the NO_x SIP Call program showed that significant reductions in NO_x emissions and ozone transport downwind in Canada would occur. Along with information as to what emissions would be without the NO_x SIP reductions, this information was crucial for Canadian governments when presented with the decision about whether to move toward a negotiated agreement. Maps of NO_x emissions densities for the Eastern US and Canada for 1995 showed that in the transborder region, the areas of highest emissions densities were along the Canada-US border and along the Atlantic coast in the US. More importantly, these twin corridors of dense population and precursor emissions run from the southwest to the northeast, in parallel to the weather pattern that frequently occur in the summer. This information was to some extent new to the US, since previous US analyses had not mapped out the Canadian-side densities for ozone and its precursors.

In order to communicate with the decision-makers, it was necessary to convey these transboundary issues in a clear manner. One method was to show ambient ozone concentrations from monitoring data taken during regional ozone episodes that had occurred in the eastern Canada-US region. In the joint Ozone Transport Report, for instance, the "movement" of the ozone across the border during the July 1995 ozone episode was illustrated through freeze-frame pictures of the movements of an ozone episode over the course of the day. While this was relatively low tech, it provided an easily understandable picture of transport for the policymakers. Another useful tool was joint modeling of emission reduction scenarios for 2007 – one scenario without any additional controls, and a second scenario with NO_x reductions – in order

to demonstrate the likely change in air quality with emission reductions in both the US and Canada. The joint model was able to illustrate a potential reduction in concentrations from the implementation of abatement strategies.

According to Barton, because the annex included specific obligations, the agreement reached, the Ozone Annex, was not a "fuzzy" agreement, as other international environmental agreements have tended to be. In fact, during the process of negotiation, the Canadian government actually created new domestic measures that would make it easier for Canada to implement policies to meet its obligations under the Annex. In addition to the commitments to control measures by the US and Canada, the Annex also covered several areas of scientific and technical commitments, including provisions for monitoring and assessment with the US-Canada joint tools and for reporting. The monitoring and assessment commitments range from tracking health and environmental changes to expanding facility-specific emissions data in both countries. Reporting is another important component of the Ozone Annex. Beginning in 2004, annual and ozone season NO_x and VOC emissions will be reported in biennial reports using a common format. In 2002, ambient air quality data will be shared for all relevant monitors within 500 km of the border, also using a common format. Finally, from 2004, in order to ensure that reduction measures are actually happening, biennial reports will provide information on the implementation of the Ozone Annex controls.

In conclusion, Barton indicated that the joint tools that were effective in addressing transboundary issues for ozone could also move the agenda on PM. They are expecting to have a picture of PM transport drawn by 2004 and have something to move on by the "revisit" date for the Ozone Annex. The success of moving the PM agenda, however, depends on the development and implementation of programs both in the US and Canada as well as the political will of both sides.

Long Range Transport Chair, Terry Keating, EPA

Mario Molina, MIT, *Impact on Air Quality of Industrial Globalization and Long-range Transport of Pollutants.* In his discussion of long-range transport issues, Molina focused on a recent report, "Global Air Quality," that came out of the Committee on Atmospheric Chemistry of the NRC and an IPCC report on climate change. There are questions about what might happen toward the end of the century if human activities continue along their current path. Also, the atmospheric chemistry community needs to look at the changes in the chemistry of the global atmosphere, regardless of the implications for climate change. According to Molina, the connections between climate change and air quality are clear, but the mechanisms need to be better understood. He highlighted some examples of where this contribution was needed.

Several scenarios for tropospheric ozone were developed including some with substantial increases in NO_x emissions. Since impacts of NO_x emissions on the global radiative balance are not well understood and, on a longer time scale, there could be a net cooling from NO_x emissions, atmospheric chemists should review the assumptions behind these scenarios. Similarly, in a report entitled "Global Climate of the 21st Century," the expected temperature changes ranged from one or two to around six degrees. However, the report used the relatively optimistic (and still questionable) assumption that emissions of SO_2 would go down. Because this assumption holds strong implications for the levels of temperature increases that could occur, atmospheric chemists should revisit this assumption. Also, looking at maps of ozone levels across the US, studies have indicated that the increases in O_3 reflect increases in the levels of emissions coming from Asia to the western US. While this is one possibility, there is still considerable uncertainty regarding this possible scenario. Another crucial question relates to the possibility that rising temperatures could be an important driver of ozone values. This work showed that although ozone could increase from 39 to 64 ppb, these values fail to consider the expected increase in temperature, which would be a negative feedback to stabilize the system by raising the water vapor level.

A better framework is needed to address questions about global air quality changes. Many of the human activities that are contributing to these major changes in climate and the chemistry of the atmosphere are likely to continue on their own, and in the absence of a concentrated effort to mitigate these future emissions, these projections will be "observations" on a longer time scale. However, one of the critical findings of the Committee's report is that current observational systems are not adequate for characterizing many important medium-term and long-term global changes. There is no clear mandate to lead US research

efforts to make these types of observations, with one of the core institutional problems being the confusion about which single agency would be responsible for developing these types of needed observational networks.

In conclusion, there are few purely local problems. While there are some chemical species, which we thought would be important only locally, it is becoming clear that even the fairly short-lived species, if produced in large enough amounts, can cause problems on the regional and even global level. Therefore, we need new ways of thinking about international and longer-term implications of these local phenomena, in order to avoid global problems.

Terry Keating, EPA, *Summary of June 2001 Conference on the Transport of Pollution from North America to Europe.* In June 2001, the EPA sponsored a meeting entitled: "Photooxidants, Particles, and Haze Across the Arctic and North Atlantic: Transport Observations and Models" at the Center for International Earth Science Network in Palisades, New York (CIESN). CIESN provided a neutral ground for the discussion, and was a good place for information sharing and for collaboration. One of the purposes of this workshop was to bring together three overlapping communities: the global, the international, and the regional air quality science communities. Approximately sixty workshop participants came from ten organizations including Environment Canada, EUROTRAC, AMAP, and NASA, and represented a range of countries from North America and northern Europe. The workshop reviewed many past field programs from 1980 to the present, and then looked ahead to the work of future field activities being planned for studying Pacific, Atlantic, European and Trans-Eurasian transport. The participants reviewed the modeling tools – regional, hemispheric and global air quality models – being used at various levels. Modeling results show a substantial contribution of background ozone in the US from Asia and Europe, approximately 7 ppbv. The workshop report also pointed to the expected changes in the global distribution of emissions, noting that future emissions control programs in North America and Europe and developmental priorities in Asia will increase the significance of intercontinental transport. Intercontinental transport of pollutants is important with respect to accumulated pollutant exposure. As air quality standards and objectives are made more stringent, the contribution of intercontinental transport to exceedances of those objectives will increase.

Several recommendations came out of the workshop for model evaluation, long-term monitoring, intensive observational studies, emissions inventory development, linkages to climate, and communication and collaboration. First, the priorities for model evaluation included development of a plan for targeted evaluation of the ability of models to simulate intercontinental transport events and long-term hemispheric trends. Long-term monitoring was the second area of recommendations. Researchers should not only continue to use what is already out there, but also invest further in maintaining and enhancing existing observation networks. Priority should be given to those sites and techniques that will help researchers get a good vertical profile. In addition to making effective use of satellite-based and ground-based remote sensors and capture the potential platforms of opportunity, there is also a need for intensive field campaigns. Recommendations for increased collaboration included improving the compatibility or documentation of formats for data sets, establishing meta-data catalogues and reviews, and supporting the development of accessible, distributed archives and retrieval software. NARSTO, for example, has a data archive, which shows that we can share data without making massive investments.

Greg Carmichael, University of Iowa, *The Impact of Asian Emissions on Local/Regional/Global Air Quality.* In Asia, rapidly growing populations are generating huge energy consumption needs. While Asia's energy consumption was estimated to be 20% of the world total, by 2020 that share could grow to 30%. Furthermore, coal is the fuel driving growth in these economies, meaning that sulfur emissions may follow the same substantial growth rates. Looking at sulfur deposition in 1990 and projections for 2025 and 2050, calculated from the MATCH model using "Conventional Development Scenario" emissions, most of Asia lies in the range of 1000-5000 mg/m^2 per year, even reaching 5000-9999 mg/m^2 per year over large areas. From past experience in Europe, major ecological damage is seen at these levels of deposition. Looking to the potential sulfur deposition rates of Asia, future levels are expected to be extremely high.

Several regional air pollution issues are beginning to emerge, with the effects of long-range transport from northern China being felt not only in neighbors such as Korea and Japan, but even in North America.

Trans-boundary pollution issues are of growing importance in Asia. Japan is increasingly becoming a receptor of emissions from other Asian countries. To illustrate, China's contribution to sulfur deposition in Japan has increased from 20% to 35-40% between 1975 and 2000. In the winter, the Asian plume of NO_x is important, but all emitters are contributing to the ozone levels in the Pacific Basin. Over central California the Asian contribution to total ambient ozone at the surface averaged from 3 to 4 ppb in 1990, but scenarios indicate that this could shift up to values of about 20 ppb in 2020. Regarding other trace elements from coal combustion, with growing coal use, mercury becomes an important consideration for transport.

Carmichael raised the issue of whether this was a cause for pessimism, suggesting that there are some signs of improvement. For example, China's State Environmental Protection Administration (SEPA) estimates that economic losses due to acid rain damage to forests and farmland are on the order of $13.24 billion annually. These impacts have lead to action, and in 1999, Xiangtan, China, received over 2 million Yuan in compensation from the neighboring cities due to the yellowing of paddy fields. Looking at SEPA emissions estimates for SO_2, emissions levels have actually gone down since 1996. While it seems that there has been a remarkable change in air pollution emissions in China, the question that remains is whether these reductions can be sustained. Most of this change was related to the economic downturn in 1997 and 1998 in East and Southeast Asia, and other factors such as reforms of industry and power, leading to a reduction in coal use, slowdown in electricity demand, due to higher prices, and structural shifts away from heavy industry towards high-tech industries and services.

Although China is a major player, India and Southeast Asia are on the rise, meaning that soon it will not be just China which is the dominant player. Sulfur emissions in Asia are changing, region by region, in different ways. Carmichael also noted the importance of factoring in interannual meteorological variability, since its effects on sulfur deposition can be much larger than the effect of changes in emissions.

Glen Cass, Georgia Tech, *Long range PM transport from India.* Cass noted that during this symposium, mention has been made of the INDOEX experiment about which he would be talking today. The INDOEX study, with dozens of co-investigators involved, focuses on pollution in the Indian Ocean using a variety of measurement platforms including aircraft, ships geostationary satellites and ground-based platforms for measurements. A major ground-based platform is the new Kaashidhoo Climate Observatory. A news release from the Scripps Oceanographic Institute on the Kaashidhoo Climate Observatory pointed out that the island was chosen for its remote location and pristine environment. Boat traffic to and from the island is minimal and tourism does not exist. The observatory's location on the northeast tip of the island also protects it from local pollution from domestic burning and small motor cycles, which are restricted to another portion of the island. So measurements of fine particles on Kaashidhoo Island in the INDOEX study were initially run for 48 hours at a stretch in order to obtain a large enough sample for analysis. Yet, in looking at the samplers the investigators soon discovered that samples could often have been collected for just four hours, as the island was not nearly as clean as researchers had anticipated. Both high pollution and low pollution events were observed. Following the backward trajectory – typically a 10-day transport – of air parcels arriving at Kasshidhoo Island, one observed very different transport trajectories for high pollution and low pollution events. On the high pollution event, air parcels were traced back to India, while the low pollution event air parcels traced back across Myanmar, Thailand and Cambodia. In fact, looking at the time series of fine particle (D_a<1.8μm) mass concentration for February 11-26, 1999, concentrations on this remote island averaged around 17-18 $\mu g/m^3$ with a high of nearly 25 $\mu g/m^3$, almost as high as what would be found in Los Angeles.

The Integrated Aerosol Optical Depth was mapped out for the region as a measure of air quality, with low values of 0.05-0.10 indicating relatively clean air. As one moves further north into the Indian subcontinent these values can go as high as 0.4 and 0.5. What is remarkable, however, is how these areas of high values for the integrated aerosol optical depth extend over a very broad region. The chemical contributors to the aerosol optical depth include sulfate (26%), sea salt and NO_2 (11%), organics (17%), mineral dust (12%) and ash (7%). Black carbon (BC) is also a contributor (11%). In the INDOEX study, the black carbon concentration had a high ratio of BC/OC (OC = organic carbon), ranging from ½ to almost 1 by all measurements.

One remaining puzzle is to identify where is the BC coming from. While the INDOEX measurements can trace back trajectories of air parcels for up to 10 days, what is unknown is what happened at the start of those 10 days and what were the initial conditions for those outflows. Calculations suggest that the concentration levels of black carbon might be more than 100 $\mu g/m^3$ at the source to be able to show those levels of concentrations after 10 days of transport. In answer to a question at the end of the talk as to what might produce such particles, Cass replied that there are actually few emissions sources that emit such high ratios of BC/OC. The two main contenders are diesel engines and inefficient, low temperature coal burners. Some speculate that it is biomass combustion, but with biomass one does not see the same ratios of BC to OC. All of the INDOEX results indicate that something different is going on in India, as the levels in China do not show nearly the same levels of black carbon.

What are highest priority topics for a research agenda? Discussion led by Mario Molina, MIT.
According to Barton, one of the important issues was the collaboration of the US with the countries that they believe to be the originators of emissions leading to rising concentrations in the US. One question, Barton went on to say, is if the research agenda can be crafted to begin to put money into China or India. In that way, these countries could be collecting their own data and therefore would believe the results, rather than accepting the results of US-based research that points to their emissions as long-range transport problems. Molina agreed that there is a need to establish such mechanisms for international collaboration on measurements, raising the question of what possibilities there are for more formal mechanisms to achieve this goal. How could one more systematically link the work that was just presented on transport from India to that conducted in India to study local emissions and their impacts?

Molina also highlighted the importance of placing these problems in perspective, by better linking emissions and concentrations to health effects. There are a broad range of concerns, and differing public attitudes toward the impacts of emissions and their transport. On the one hand, there are concerns about visibility in the national parks, and on the other hand we are also concerned with terrible urban air pollution in urban centers in the developing world. How do scientists prioritize research to reflect these disparate impacts on the environment and public health? Given the enormous health risks posed by emissions in developing country megacities, can the developed world make a more concerted effort to get involved and promote research on these issues in the developing world?

As noted by Dickerson, collaboration between the developed and developing world has many obstacles to overcome, as there are often wide differences in information needs and capabilities between the developed and developing world. Moreover, in investigating global problems, differences in measurements make modeling any global phenomena highly difficult. For example, in order to run a global model one needs information from the developing world, yet the developing world is often not using the same techniques and the same measurements and emissions inventories. For future research, it was suggested that improving emissions inventories were critical, yet it was recognized that it is difficult to envision American-style emissions inventory in countries such as India. Therefore, we need to improve our ability to infer emissions from the other data that do exist. In the end one needs to do some direct measurements, are necessary, but one can complement and validate those data with other approaches.

According to Farrell, one area for future research relates to the methods and modes of technology substitution and the development of new technologies that can begin to address these issues of air quality and climate change. We need to consider how immediate and how urgent is it to address problems by developing and deploying new technologies. Molina replied that one issue that captures this is biomass burning.

Stepping back to global level problems, Molina observed that what really drives the international dialogue is the climate change issue. Therefore, we need to look at what the role of air quality is in that debate. Molina then raised the issue of whether development is good or bad, which has emerged as a central issue in the climate change dialogue. As we are seeing in Mexico City now, as developing countries grow, they can begin to afford to pay for air quality. The question is whether they can learn from the mistakes made in the developed world. The challenge is to work together to avoid following destructive pathways.