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Integrated Assessments: Using Regional Models to Evaluate Health Impacts of Air Pollution in the United States and China

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1. INTRODUCTION

The objective of our group is to utilize science to inform air quality policy. Scientific and policy problems can no longer be addressed exclusively from a single disciplinary viewpoint. The complex dynamics of strongly interacting processes require scientists and decision makers to think and act in a more integrative manner. It is critical that scientific knowledge and tools be used to inform policy decisions. An integrated assessment approach that examines the impacts of air quality on society uses scientific information to examine the consequences of the emissions of air pollutants on human health and welfare and estimates the economic value of these impacts. The purpose of the assessment is to inform decisions on how to best control pollutant emissions in a way that protects human health and welfare at minimum cost. We are using an integrated assessment approach to examine the impact of air quality on health in the United States and China in order to illuminate improved air pollution control strategies.

Figure 1 gives a schematic outline of the components in our integrated assessments. Three projects, which are described below in more detail in sections 2, 3, and 4, are integrated assessments that utilize Models-3 to calculate air quality. The calculations are compared with available data to evaluate the model accuracy and are then used, in conjunction with population distribution data as input to epidemiological exposure-response functions to evaluate health impacts. Future work will include quantifying the value of the damage done to human health and welfare of the calculated pollution levels and, based on the findings, proposing alternative regulatory strategies.

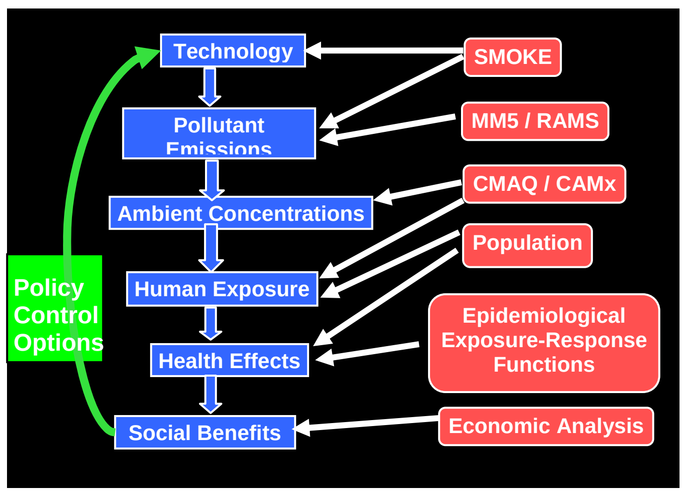

Figure 1. Integrated Assessment Approach. Blue indicates the conceptual link between the components of the integrated assessment while red indicates the tools used. Green shows the possible policy feedback resulting from the findings of the technical analysis.

2.0 HEALTH DAMAGE RESULTING FROM O_3 PRODUCED BY NO_x POINT SOURCES: An exploratory analysis of issues associated with emissions trading

We examine observational O_3 data from the EPA-AIRS network to determine whether the NOx

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cap-and-trade program implemented in the eastern United States was successful in its objective of reducing O_3 concentrations to acceptable levels. The program capped NOx emissions in 1999 at levels less than 50% of what was emitted in the 1990 baseline year, but permitted free trading between May and September inclusive, regardless of local temperature, biogenic hydrocarbon emissions or proximity to population centers. Figure 2 shows qqnorm plots of 8-hour maximum O_3 surface concentrations prior to (black) and after (red) the cap went into effect in 1999. The figure indicates little reduction in surface O_3 concentrations in the north-eastern U.S. where in summer exceedances of the 80ppb 8-hr. standard still frequently occur.

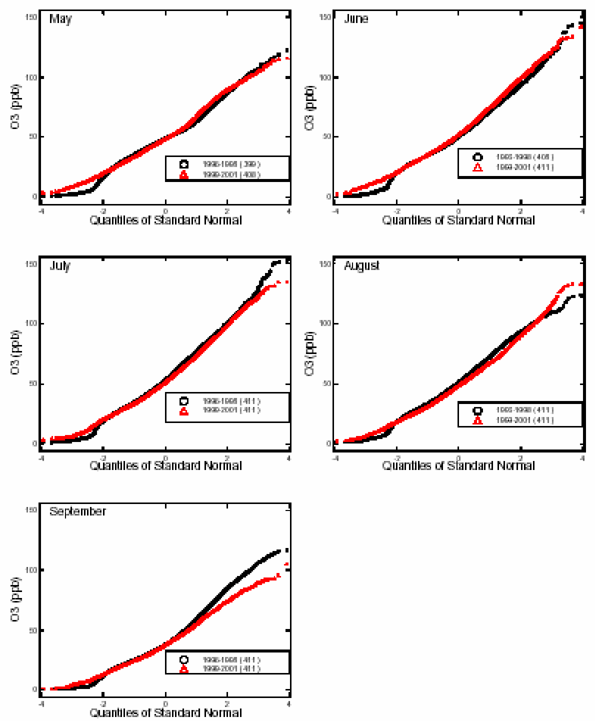

Figure 2. QQnorm plots of EPA-AIRS surface 8-hour maximum daily O3 observations in the north-eastern United States prior to (1995-1998) and post (1999-2001) the NOx emissions cap, in black and red, respectively.

2.1 Effect of changes in temperature and biogenic emissions on O3 production and mortalities.

To examine the possibility that the spatial and temporal flexibility permitted in emission trades during the May-September O_3 season might have contributed to the small reduction in O_3 concentrations observed after the cap, we used CAMx (we are presently converting to the use of CMAQ) to simulate several cases. We conduct a standard simulation during July 1995 where actual emissions for the period are used. We next reduce the emissions from a single power plant by $1.77x10^6$ moles NOx for 24-hours during a period of low and high temperatures to evaluate the different amount of O_3 the NOx from that power plant would have produced had it been emitted under the different temperature conditions. We find a greater amount of O_3 is produced during the warm than the relatively cool period. We then use the population distribution in the affected area in conjunction with an exposure-response function for O_3 [Samet, J. M. et al., 1997] to calculate the resulting mortalities and find 0.17 mortalities occurred during the high temperature period compared with a slight decrease in mortalities resulting from a reduction in O_3 concentrations due to titration of O_3 with NO over high population areas during the low temperature period. Figures 3a-d show these results.

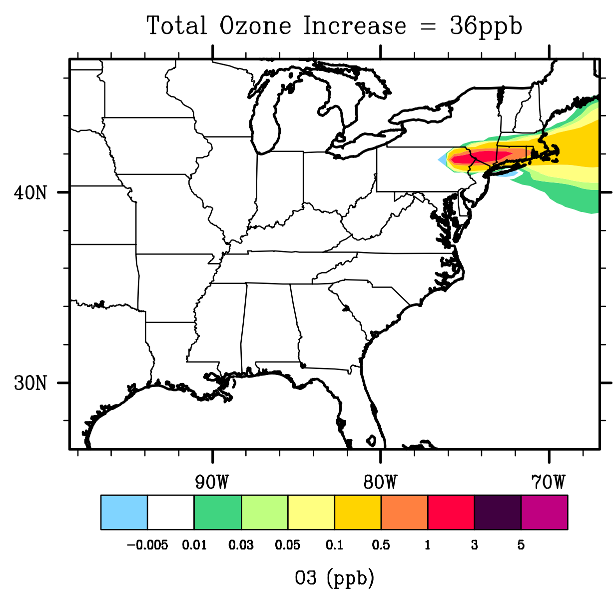

Figure 3a. Total ozone increase in a period with high mean temperature (302K +/- 3.6 K (83.5F)) due to 24-hour of emissions from a single power-plant.

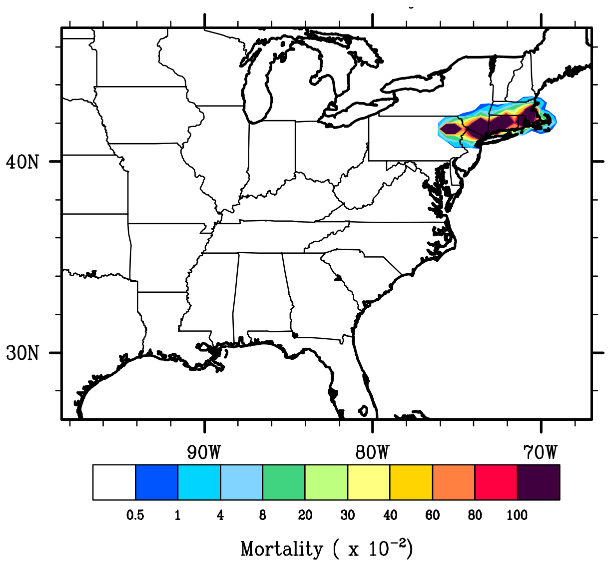

Figure 3b. Mortalities resulting from O_3 formed from 24-hours of NOx emitted from a single power plant during period of elevated temperature in 3a. Total increase in mortality = 0.17 deaths.

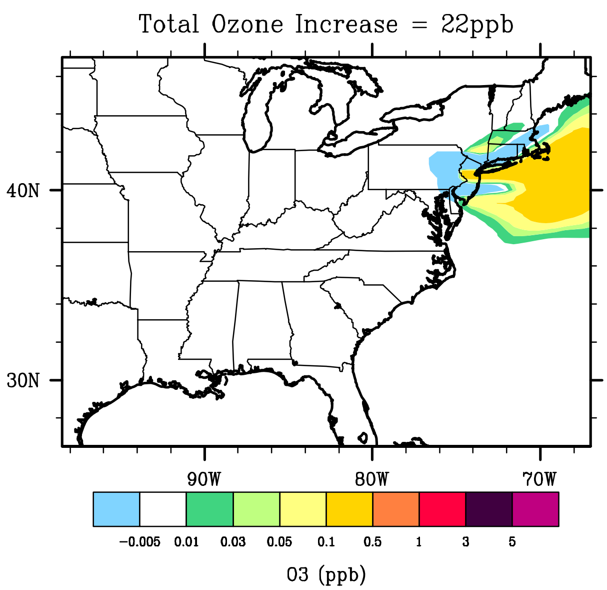

Figure 3c. Total ozone increase in a period with relatively low mean temperatures = 296K +/- 4.3 K (72F). Note regions over high population centers in which O_3 concentrations actually decrease.

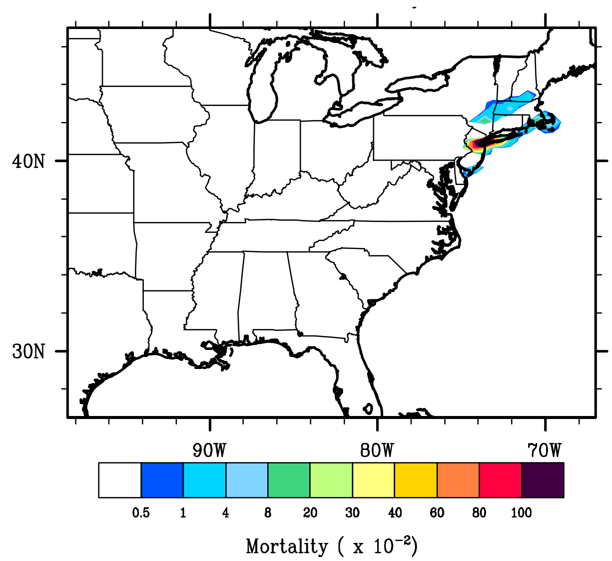

Figure 3d. Same as 3b except mortalities for cool temperature period shown in 3c. Total mortality change is negligible.

Likewise, in a similar set of simulations, we find much greater O_3 production occurred in a region of high rather than low biogenic isoprene emissions. Finally, we examine the mortalities that result from O_3 produced from the same quantity of NOx emitted in a region upwind from high and low population centers. We find greater mortalities resulting in the high population case (though the wind direction can have a substantial effect in determining the affected locations) than the low population region. Thus it is clear that a NOx emissions trading program that does not restrict trades based on any spatial or temporal dimension is likely to result in higher O_3 concentrations and higher resulting mortalities than one in which trades from high to low temperature periods, from high to low biogenic emission regions and downwind rather than upwind of population centers were preferred.

3. DEVELOPMENT OF AN EMISSION INVENTORY FOR THE SHANDONG REGION OF CHINA

Emissions are a critical factor in accurate air quality simulations. Our objective is to examine the effects that improvements in air quality would have on human health in the Shandong region of China (shown in Figure4). These improvements could result from changes in emissions due to the use of different energy and environmental control technologies. In order to examine the improvements that such technological changes could bring, we developed a high-resolution emission inventory based on activity data at a sub-provincial level within the region for the year 2000.

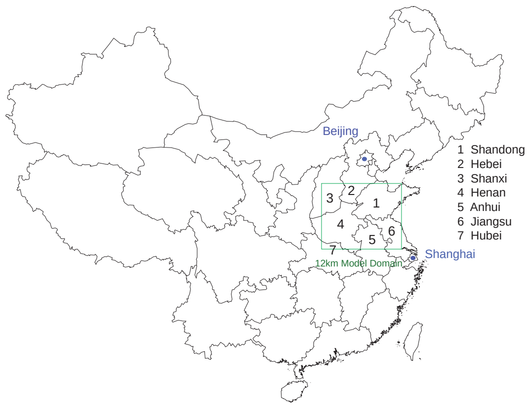

Figure 4. Map showing the simulated area outlined in green. The area inside the outline includes the sections of provinces for which we compiled an emission inventory.

To estimate annual emissions, we use the product of annual rates of emission-related activities and respective emission factors, differentiated by chemical species, municipality, economic sector or sub-sector, fuel or activity type and abatement technology. The resulting emissions are in the form of annual emissions for a specific chemical species, municipality and source classification code (SCC). The emissions are defined as:

$$E_{j,k} = \sum_{l}\sum_{m}\sum_{n} A_{j,k,l,m,n} EF_{j,k,l,m,n}$$

Where, E = emissions, A=activity rate, EF= emission factor, j=species, k=municipality, l=sector or sub-sector, m=fuel or activity type, and n=abatement technology. Data was collected primarily from Chinese official statistics[National Bureau of Statistics of China, 1999: Shandong Statistics Bureau, 2001: Statistical Bureau of Anhui, 2001: Statistical Bureau of Hebei, 2001: Statistical Bureau of Henan, 2001: Statistical Bureau of Jiangsu, 2001]. Figure 5 shows the methodology used to compile total emissions for each city from fuel consumed and emission factors for each sector and each chemical species. The SMOKE modeling system is then used to process the spatial and temporal allocation and chemical speciation of the Shandong region emission inventory including both diurnal and seasonal variation in emissions.

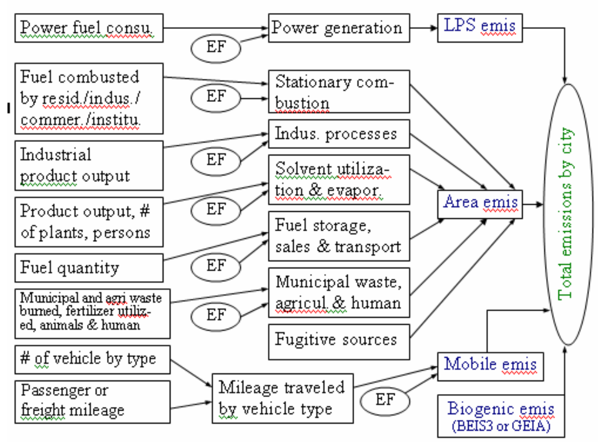

Figure 5. Methodology used to compile a regional emission inventory .

3.1 CMAQ SIMULATION AND EVALUATION

We run a simulation of the Shandong region using CMAQ with input from the emission inventory described above and MM5-generated meteorology. To evaluate the accuracy of our emission inventory and simulation, we compare the model results with observational data obtained from the National Air Quality Monitoring Network of China and data from the provincial environmental authorities both of which make public daily air quality reports available online. Comparisons of observations with model simulated concentrations of PM10 and SO_2 are shown in Figure 6. In general, the simulated concentrations are slightly to significantly lower than observations. This is expected because our current inventory includes anthropogenic emissions only and no biogenic emissions or desert dust. Biogenic emissions are currently being incorporated. In addition, the model appears to underestimate SO_2 concentrations in winter when dispersed coal burning for heating takes place in many medium- or small-sized cities of this region. This may be due to underestimates in the official statistics of SO_2 emissions.

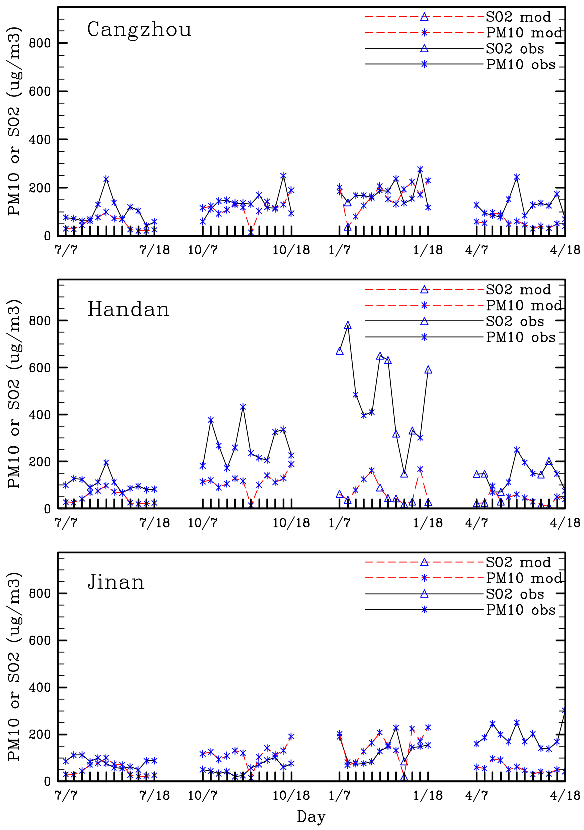

Figure 6 Comparison of simulated city-averaged PM10 and SO2 concentrations (red lines) with corresponding observations (black lines).

An evaluation of the health and economic impacts of the simulated pollution loadings will be completed shortly and are expected to provide a conservative estimate of the impact of air pollution on health.

4. ROLE OF MODELS-3 IN THE DEVELOPMENT OF AN INTEGRATED ASSESSMENT MODEL TO EVALUATE U.S. AIR POLLUTION IMPACTS ON HEALTH

This project builds on the previous two projects and is being conducted in collaboration with Prof. Robert Mendelsohn of Yale University. It aims to measure the potential damage of air pollution to public health in the United States so that estimates of damages caused by pollution can be included in the national accounts. To achieve this objective, we are assembling various models available from different communities, including EPA Models-3 for atmospheric chemistry and transport, health and economic assessment tools to create an integrated assessment model to quantify the damage caused by air pollution over the continental United States. The architecture of the planned integrated assessment model is shown in Figure 7.

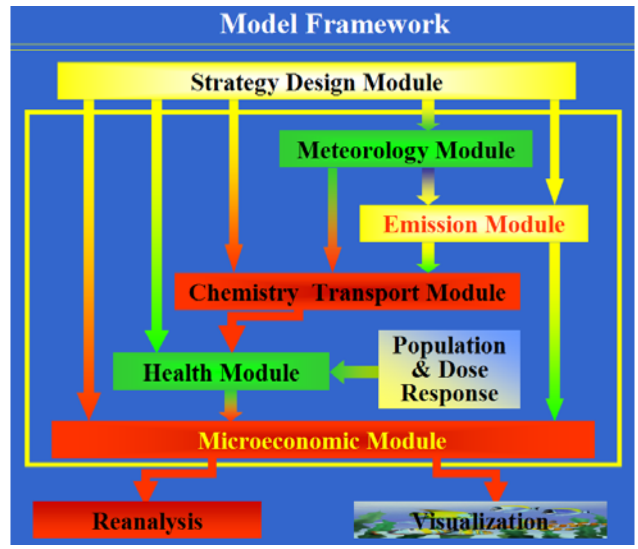

Figure 7. Architecture of proposed integrated assessment model.

The integrated assessment model will consist of essential components which require the expertise of very different technical disciplines. The model will be used to bridge the previously independent communities of atmospheric science, epidemiology and economics in order to make clear the consequences of emissions on health and resulting costs. The model will provide a platform whereby each discipline can contribute their expertise to address the total problem more efficiently.

Various models from different scientific communities have been assembled or are being developed to provide a working chain that simulates the final image of the integrated assessment model. The model will be designed in a modular fashion so that it will be able to keep up with advances in different disciplines. To facilitate this, we have chosen state-of the-art modules from each field. The UCAR/PSU Mesoscale Meteorology (MM5) model has been selected as meteorology module. MCNC SMOKE will be applied to deal with emission processing. EPA Models-3/CMAQ is employed to address chemistry and transport of the pollutants of concern. We are also developing a health module to quantify and monetize health damages and associated costs of air pollution. The health module takes population census and other GIS information, results of dose response studies, as well as output of air quality modules as input, and provides quantitative estimates of health impacts. A current prototype of our health module (used in the project described in section 2) presently takes mortality due to ozone exposure into account. Additional species, including PM2.5 and SO_2, will be added to the module in the future. Yale is taking the lead on analysis of the epidemiological data that will be used to develop the health module.

One key issue to make the integrated modeling system work is the compatibility of individual components. Some of the components are well tuned to interact with each other, such as MM5, SMOKE, and CMAQ. But that is not the case for other components. For those where compatible models are not available, we will either develop a new module, for instance, the strategy design and health modules, or provide interfaces to interact with different models.

An early stage of the modeling system is currently running on a Beowulf Linux cluster at Princeton University. The cluster consists of 1 master node and 32 computing nodes, each of which has two 2.4GHz CPUs, 2 GB DDR, and is inter-connected by fast Ethernet or Gigabit switches. A Portland Fortran compiler is used to compile and run Models-3 and the necessary libraries such as message passing, IOAPI and netCDF. The main data stream throughout the integrated model, except inside Models-3, is built on the netCDF file format using the Java netCDF library to enable remote data communication and graphic data presentation.

We anticipate that this model will provide a valuable future tool to community efforts to evaluate the effects of air pollution on health and the associated costs to society in a scientifically rigorous fashion.

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