NCER Assistance Agreement Final Report

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Title: Implications of Climate Change for Regional Air Pollution, Health Effects and Energy Consumption Behavior

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Research Category: Assessing the Consequences of Interactions between Human Activities and a Changing Climate

Project Period: 02/08/2001 – 02/07/2004 (no-cost extension granted through January 2005)

Description and Objective of Research:

This research program has four major modeling elements: climate change and variability, electrical energy demand and production, regional air pollution, and human health effects associated with air pollution exposure. Our overall objective is to develop a scientifically credible modeling facility that will help policy makers and analysts understand the effects of human activities on climate change and variability as well as the possible human responses and adaptations to climate change and variability.

Summary of Findings:

Joutz and Crowley: We investigated climate change-driven effects on electricity demand. The research focused on the estimating the impact of higher temperatures on electricity consumption using hourly data and annual data. The Pennsylvania-New Jersey-Maryland (PJM) Independent System Operating (ISO) or mid-Atlantic council region of the North American Electric Reliability council was primary area for the study. Additional data was used from the East Central Area Reliability (ECAR) and Southeastern Electric Reliability council (SERC).

Scenarios were constructed to present the impact of a 2 degree Fahrenheit increase in temperatures. Short-run and long-run models were used in generating the scenarios.

The short-run models were constructed to estimate the sensitivity of the daily load curve to hourly temperature for all ten load regions in the PJM separately. The responses are conditional on a given stock of electricity using equipment, building shell efficiencies, stock of electricity generation facilities, and transmission network. Simulations were run to examine the effect of the temperature increase. These short-run models are especially useful for their detail and relating peak loads and changes in the load curve or human response in terms of electricity demand.

The long-run model results are based on a "general equilibrium approach" for the entire U.S. The National Energy Modeling System (NEMS) which the Energy Information Administration (EIA) uses in making projections to 2025-2030 was the primary model. In the NEMS, households and firms can adjust stock of electricity using equipment and building shell efficiencies in response to relative prices, economic activity, and technology choices. Similarly, the electric utility sector adjust the mix and stock of generating facilities and transmission network in response to expected demand, relative prices of input sources, technology, and regulatory environment.

The output from the short-run and long-run consumption models in terms of load projections and elasticities serve as the inputs to supply side models which allocate or dispatch the electricity from the generation stock and mix to meet the load. Given the dispatch assumptions, that model will project with electricity sector emissions, with a focus on NO_x. Climate change will alter the level and timing of electricity demands, as well as the thermal efficiency of electricity generating units. With a given capital stock of generating plant (short run analysis), this will change their operations and emissions. Even in the presence of seasonal or annual emissions caps, emissions might then increase during the warmest days when ozone episodes are most likely to occur. In the long run, the mix and amounts of various types of generation technologies will adjust, and if climate change occurs, the resulting generation plant will be different than if climate change does not occur. This has further implications for the timing and amount of emissions. This portion of the research project developed and demonstrated methods for obtaining temporal and spatial distributions of NO_x emissions from power plants, and for quantifying the effects of climate change scenarios on those distributions.

In Section 1 of the full report (see http://www.ce.jhu.edu/epastar2000, Energy Demand link) we provide background on the analyses of weather effects on electricity consumption. In addition we briefly describe the data used in the analysis. The next section explains the methodology and models used in the short-run (hourly) responses of electricity consumption to changes in temperature. Section 3 contains results on the potential long-run impacts of temperature on electricity loads. Two different modeling approaches were used. The first is based on the U.S. Energy Information Administration's National Energy Modeling System (NEMS) and the second is based on a regional and sectoral econometric model of electricity consumption. In Section 4, the database programs used in the analysis are briefly described so that the work may be replicated. The final section provides other explicit accomplishments of this research projects. All material is provided in electronic format on a CD by section.

<u>Hobbs and Chen:</u> The purpose of this portion of the project is to link electricity demands with electricity sector emissions, with a focus on NO_x. Climate change will alter the level and timing of electricity demands, as well as the thermal efficiency of electricity generating units. With a given capital stock of generating plant (short run analysis), this will change their operations and emissions. Even in the presence of seasonal or annual emissions caps, emissions might then increase during the warmest days when ozone episodes are most likely to occur. In the long run, the mix and amounts of various types of generation technologies will adjust, and if climate change occurs, the resulting generation plant will be different than if climate change does not occur. This has further implications for the timing and amount of emissions. This portion of the research project developed and demonstrated methods for obtaining temporal and spatial distributions of NO_x emissions from power plants, and for quantifying the effects of climate change scenarios on those distributions.

In Section 1 of the full report (see http://www.ce.jhu.edu/epastar2000, Generation and Dispatch link) we provide background on the analyses, as well as summarize data sources. In Section 2, we describe the methodology used to assess the effects of climate warming assuming short-run (fixed capital) conditions for the power generation sector; this is an emissions- and transmission-constrained representation of the power market for the mid-Atlantic and Midwest states. Generation plant and demand conditions for the year 2000 were used in that analysis. That section also summarizes the results of the analysis. In Section 3, we turn to the issue of interannual variability of climate, electricity demands, and emissions. Most energy models, when used in climate impact analyses, assume a "typical" or "average" year. However, interannual variability is very important; because of the nonlinear relationships between temperatures, emissions, and their impacts, the average impact on air quality over a number of years may be quite different (and higher) than the impact on air quality in an average year. In Section 4, the procedure used to calculate long run (variable generation plant) scenarios that adapt to changing climate is described, along with selected results. Appendix I summarizes the procedure used to translate the hourly emissions outputs from the electricity generation simulation model into the script files that can be used by the SMOKE module of CMAQ. Appendix II lists publications and conference presentations from this portion of the project, and Appendix III summarizes two journal articles resulting from this project that describe the short run models and some analyses of the interaction of oligopolistic generator behavior and emissions.

The major findings concerning the short- and long-run effects of climate change on pollution emissions from the power sector are summarized as follows:

1. In the short-run, climate change, which is characterized as an increase in ambient temperatures, can affect power system in two ways: increasing power demand (demand effect) and degrading generation heat rates (efficiency effect). According to our analysis, for a 2°F increase in the ambient temperature, the former is greater than the latter by an order of magnitude. For instance, for one ozone episode analyzed, the demand effect contributes a 5% increase in NO_x emissions during ozone episodes, while the efficiency effect accounts for less than 0.1%. These increases occurred even though emissions were assumed to be subject to a seasonal cap. The greatest emission impacts occur in the hours when demand is already high; because those are the hottest days of summer, those are also the days when ozone episodes are most like to occur (Section 2).

2. Besides the short-run demand and efficiency effects, climate change has long run effects on two categories of capital stock: energy-using equipment (e.g., size and numbers of air conditioners) and the mix and amount of generation plant (e.g., the amount of peaking gas-fired capacity versus baseloaded coal capacity). The effects on consumer equipment choices are examined in the GWU portion of this final report. Here, we focus on effects on generation investment, and the implications for emissions. We used a combination of the GWU short-run analyses and long run National Energy Modeling System analyses to analyze the effect of a 415 ^{o}F-day increase in cooling degree-days upon electric load distributions in the year 2025. As a result, we project the highest (peak) hourly demand increases by 11%, compared with just a 4.5% increase in the summer average demand. The CDD increase was obtained by analyzing selected years from the GISS GCM/MM5 scenarios for the 1990s and 2050s climates. The substantial increase in the peak period demand has two implications for the power system and its emissions. First, more peaking units such as combustion turbine need to be installed to meet high demand in the peak hours. Second, an increase in the emission during high-demand hours could worsen regional air quality at precisely those times when ozone episodes are most likely to occur. For a given summer hour, the correlation between temperature and emissions is around 50% to 70%. Our results imply that the aforementioned 15% increase in peak demand translates into a 33% increase in the peak pollutions emissions in the long run, even when there is a seasonal cap on emissions (Section 4).

3. There could be significant inter-year variability associated with NO_x emissions during high-demand hours in the long-run. Based of GISS simulations of two years under 1990s climate conditions and another two years under 2050s conditions, we find significant variation in the distribution of year-to-year peak emissions, even under the restrictive assumption that there is no interannual emissions banking. Higher peak ambient temperatures are associated with higher pollution emissions (Section 3 & 4).

<u>Ellis and Bell</u>: The air quality modeling system (MM5/MCIP/SMOKE/CMAQ) was subject to very thorough testing to ensure its proper functioning and ability to recreate measured ozone concentrations at selected locations. It passed those tests convincingly (see http://www.ce.jhu.edu/epastar2000, Air Quality Modeling link). We previously we were restricted (both hardware and software-related) to performing limited duration scenarios (on the order of several days long) and limited (spatial) domain scenarios. We now can successfully generate continental US scenarios for any arbitrary run length. For example, scenarios using MM5/MCIP/SMOKE/CMAQ were created for the entire US and the period May 1 through September 30 for 1990-1999 and 2050-2059 (this latter group of ten years of ozone season simulations used GISS output as input to regridder in MM5). In MM5, these runs were first made for a 108km domain and then nested to

36km, which was subsequently fed to MCIP, SMOKE and CMAQ. The various scripts used to run these scenarios are provided in the air quality modeling section of the project we site (see http://www.ce.jhu.edu/epastar2000). We successfully integrated revised emissions fields generated by Hobbs and Chen into SMOKE and subsequently CMAQ. We eventually settled on the process described in Appendix 1 of the full report from Hobbs and Chen (e.g., see the Generation and Dispatch section of the project web site) that uses SMOKE's capability to overwrite emissions inventory files on a source-specific and hour-specific basis (i.e., via PTHOUR).

A relatively recent development in performing the air quality analyses involved the move to a parallel processing environment. The computational results that we have seen are very encouraging. Whereas a one day national simulation (36km, 132x90, 15 layers, CMAQ 4.5) used to take about 4 hours to run, it now takes approximately 18 minutes using our parallel cluster and 24 dual-CPU compute nodes. Further speedups we believe are possible.

Student Support:
Three doctoral students were supported by this project.

Christian Crowley, George Washington University, PhD requirements completed, December 2005.

Yihsu Chen, Johns Hopkins University, PhD requirements will be completed early Spring 2006.

Michelle Bell, Johns Hopkins University, PhD requirements completed 2003, now, Assistant Professor of Environmental Health, School of Forestry and Environmental Studies, Yale University

Conclusions:
<u>Joutz</u>: This portion of the research project analyzed the response of electricity consumption to warming from climate change. More than 40% of energy end-use energy consumption is related to heating and cooling needs in the residential and commercial sectors. The analysis examined the response in the short-run when households and businesses cannot adjust their stock of electricity using appliances and shell efficiency of buildings. In addition, the research developed long-run estimates of electricity consumption when these constraints can be responded to by substituting for more efficient equipment and technology. Our hypothesis was that warmer weather would change the annual pattern or shape of the load from winter to summer. In addition, the implied daily load could change more toward peaking periods. Higher temperatures would reduce residential and commercial demand for space heating in the winter and increase the demand for space cooling in the summer. The former is typically supplied by fossil fuels while the later is almost exclusively provided by electricity. The impact could lead to greater relative peaking capacity needs. The short-run and long-run consumption responses to warmer temperatures are used in the dispatch and generation models for calculating the emissions models. The findings can be summarized in two basic points.

1) We developed 24 hourly econometric and forecasting models using approximately eight years of data for the 10 load regions of the Mid-Atlantic Advisory Council of PJM ISO. The models are based on winter and summer seasons with deterministic terms for days of the week and holidays, a cubic function for temperature, and autoregressive components for earlier hours and days. A simulation of a 2°F increase in temperature for July and August 2000 resulted in a 4.6% increase in electricity demand for the region as a whole. These being the peak cooling demand months, the average increase over the year would likely be somewhat lower. The estimates suggest that consumption was particularly sensitive to morning and late afternoon effect of temperature increases. The midday or peak hours may not have appeared as sensitive because of generation and transmission constraints.

2) Long-run warming scenarios were simulated using the U.S. Energy Information Administration’s national Energy Modeling System. We constructed a scenario based on the average of the 5 warmest summers and

the 5 warmest winters relative to the remaining periods to examine the effects of a warming in temperature. This yields approximately a 2.09 degree Fahrenheit increase in CDDs and almost 4 degree Fahrenheit decrease in HDDs. These temperatures are consistent with climate change considered by the ICCG. The period for analysis of the scenarios was from 2005 to 2025. The impact of temperature warming in the summer scenario had two important effects. First, average load demand is about 2.7 percent higher in the summer months than in the NEMS reference case. Second, the load demand is not proportionately higher by load slice. Peak demand was 5.4 percent higher in the climate warming scenario. Thus, the results suggest an important impact on the load shape. Climate change will have a disproportionate effect on load in the peak periods in each load group. This may be exactly the periods when ozone is likely to be more of a problem.

Hobbs: This portion of the research project developed methods for obtaining temporal and spatial distributions of NO_x emissions from power plants based on disaggregate electricity demand projections, and for quantifying the effects of climate change scenarios on those distributions. Both short-run (fixed generation and consumer capital stock) and long-run (variable capital stock) responses of power sector emissions to climate change were simulated. Emission projection models were developed that considered transmission constraints and detailed spatial and temporal distributions of demands, as well as the possibility of strategic market behavior (oligopoly). Previous assessments of impacts of climate change on power sector emissions considered “typical” or “average” years; however, it is important to consider interannual variability because of nonlinear relationships between temperatures, emissions, and their impacts. These relationships imply that the average impact on air quality over a number of years may be quite different (and higher) than the impact on air quality in an average year. The major findings concerning the short- and long-run effects of climate change on pollution emissions from the power sector are summarized as follows:

1. The effect of climate change upon demands is approximately an order of magnitude more important effects on generator efficiency, at least for the mid-Atlantic region. For instance, for one ozone episode analyzed, the demand effect contributes a 5% increase in NO_x emissions during ozone episodes, while the efficiency effect accounts for less than 0.1%. These increases occurred even though emissions were assumed to be subject to a seasonal cap.

2. A method for generating high frequency (hourly) fluctuations of power demands that are consistent with long-run average demand response to temperature change (as calculated by the National Energy Modeling System) was used to analyze the effect of a 415 ^{o}F-day increase in cooling degree-days upon electric load distributions in the mid-Atlantic region in 2025. We projected that the highest (peak) hourly demand could increase by 11% for the mid-Atlantic region, compared with just a 4.5% growth in the summer average demand. Peak emissions increase even more. Such an emissions increase during high-demand hours could worsen regional air quality at precisely those times when ozone episodes are most likely to occur.

3. Based upon GISS/MM5 simulations of two years under 1990s climate conditions and another two years under 2050s conditions, we find significant variation in the distribution of year-to-year peak power sector emissions, especially during peak periods.

Ellis: The current generation air quality modeling system is a useful tool for generating credible ambient air quality simulations for ozone. Retrospectively, its output compare very favorable with measured concentrations over a wide range of meteorologic scenarios. The interface between electricity generation and dispatch modeling and the air quality modeling system (particularly SMOKE) works satisfactorily and provides a reasonably effective means through which the air quality effects of emissions changes can be assessed in terms of resulting ambient air quality concentrations. The interface, is however, not fully automated, which was a goal of this project. Manual intervention is limited, but required - specifically, ensuring that source and hour-specific emissions "packet" files are correctly overwritten in the master (national) point source emission inventory. The parallel implementation of CMAQ (SMOKE is not run in parallel; MM5 could be, but that has not yet been tested) is very successful with substantial speedups possible, thus opening the way for conducting more and varied analyses.

In one important respect, progress in the project fell short of what we had hoped to accomplish - specifically, the level of integration among project components (energy demand, generation and dispatch and air quality modeling). Such integration has been successfully accomplished, but much later - and with more manual intervention - than what we originally envisaged.

Publications:
C. Crowley and F.L. Joutz ,"Hourly Electricity Loads: Temperature Elasticities and Climate Change." (2003) in Proceedings: IAEE 23rd North American Conference, Mexico City, October 2003

C. Crowley and F.L. Joutz , "Hourly Electricity Loads: Temperature Elasticities and Climate Change." (updated version, 2004) submitted to Energy Studies Review, returned for revisions, July 2004

Y.H. Chen and B.F. Hobbs, "An Oligopolistic Power Market Model with Tradable NO_x Permits," *IEEE Transactions on Power Systems*, 20(1), February, 2005.

Y.H. Chen, B.F. Hobbs, T. Munson, and S. Leyffer, "A Large Scale MPEC Model of Stackelberg Leader Behavior in the Electricity, Transmission, and Allowances Market," Computational Management Science.

M. L. Bell and J. H. Ellis, Sensitivity analysis of tropospheric ozone to modified biogenic emissions for the Mid-Atlantic Region, Atmospheric Environment, 38(13), pp1879-1889, 2004.

M.L. Bell and J. H. Ellis, Comparison of the 1-Hour and 8-Hour National Ambient Air Quality Standards for Ozone Using an Air Pollution Modeling System, Journal of Air and Waste Management, Volume 53, December 2003, pp1531-1540.

Bell ML, Hobbs BF, Ellis H (2005). Metrics matter: conflicting air quality rankings from different indices of air pollution. Journal of the Air and Waste Management Association 55(1), p. 97-106.

Bell, M.L., and H. Ellis. Modeling the impacts of emissions on tropospheric ozone levels, Part I: the role of ozone precursors (VOCs and NOx). Submitted to Environmental Science and Pollution Research.

Bell, M.L., and H. Ellis. Modeling the impacts of emissions on tropospheric ozone levels, Part II: the role of anthropogenic versus biogenic emissions. Submitted to Environmental Science and Pollution Research.

Bell, M.L., and H. Ellis. Modeling the impacts of emissions on tropospheric ozone levels, Part III: linking air quality model estimates to human health effects. Submitted to Environmental Science and Pollution Research.

Bell, M.L., H. Ellis. The impact of biogenic VOC emissions on tropospheric ozone formation in the Mid-Atlantic region of the United States. Accepted for publication in Air Pollution 2005.

Presentations:
C. Crowley and F.L. Joutz, "Residential Energy Consumption: Longer Term Response to Climate Change," 24th Annual North American Conference of the US Association for Energy Economics and International Association for Energy Economics, July 8 - 10, 2004, Washington, DC

C. Crowley and F.L. Joutz, “Hourly Electricity Loads: Temperature Elasticities and Climate Change,” 23rd International Association for Energy Economics, North American Conference / VI Congreso Anual de la AMEE, October 19-21 2003, Mexico City

C. Crowley and F.L. Joutz, Seasonality and Weather Effects on Electricity Loads: Modeling and Forecasting, MetrixND Forecasters User Meeting September 23-25, 2002, San Diego, CA

Y.H. Chen and B.F. Hobbs, “Interaction of Oligopolistic Transmission Portfolio Standards, Green Gricing Programs, & Emission Allowances”, 24th Annual North American Conference of the US Association for Energy Economics and International Association for Energy Economics, July 8 - 10, 2004, Washington, DC

Y.H. Chen and B.F. Hobbs, “An Oligopolistic Electricity Market Model with Tradable NOx Permits,” 23rd International Association for Energy Economics, North American Conference / VI Congreso Anual de la AMEE, October 19-21 2003, Mexico City

Y.H. Chen, B.F. Hobbs, and F.A.M. Rijkers, “US NO_x Permits and BE-NL Market Integration: Applications of Complementarity Oligopoly Power Models,” Annual Meeting, Institute for Operations Research and Management Science, Atlanta, GA, Oct. 19-23, 2003.

Bell, M.L., H. Ellis. 2005. The impact of biogenic VOC emissions on tropospheric ozone formation in the Mid-Atlantic region of the United States. Presented at "Air Pollution 2005", Cordoba, Spain.

Bell, M.L., B.F. Hobbs, and H. Ellis (2004). Metrics matter: Conflicting air quality rankings from different indices of air pollution. Poster presentation at the 14th Annual Conference of the International Society of Exposure Analysis, Philadelphia, PA.

Supplemental Keywords: climate change and air pollution, human health, electrical energy production and demand

Relevant Web Sites

The project's web site is located at http://www.ce.jhu.edu/epastar2000. Please note that in some cases, for example, CMAQ outputs, only a sampling of output is provided on the site - a complete set of outputs is very large. For individuals wanting to obtain, for example, a full set of national layer-one CMAQ outputs for the runs that we describe, please contact Hugh Ellis (hugh.ellis@jhu.edu) and we'll work out an efficient way for the data to be transferred.