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Project Summary

Sensitivity of a Regional Oxidant Model to Variations in Climate Parameters

Ralph E. Morris, Michael W. Gery, Mei-Kao Liu, Gary E. Moore, Christopher Daley, and Stanley M. Greenfield

The continued release of CO_2 and other trace gases has in recent years led to the concern that these gases will result in the global warming of the atmosphere by blocking the escape of outgoing infrared radiation. The resultant increase in global temperature due to this so-called "greenhouse effect" may have far-reaching consequences from raising the sea level of the oceans to altering land use patterns across the globe and possibly increased photochemical smog formation in the lower troposphere.

In order to investigate the sensitivity of ozone concentrations to future climate variations, a regional oxidant model was applied for future climate scenarios to two regions: one covering central California (San Joaquin Valley, Sierra Nevada mountains and the San Francisco Bay Area) and the other covering the midwestern and southeastern United States. Based on model calculations, the effects of increased temperature on ambient ozone concentrations results in an increase of the area of exceedances of the ozone air quality standard, a movement of the peak ozone concentration closer to the urban areas, and the resultant increase in the exposure of people to harmful levels of ozone concentrations. The calculations for California indicate that the maximum daily ozone concentrations may increase from 2 to 20 percent and the number of people exposed to hourly ozone concentrations in excess of the air quality standard may triple as a result of a temperature increase. Similar, although less dramatic, results were seen for the midwestern and southeastern applications.

Past regional oxidant model simulations were analyzed to relate input meteorological variables to ozone concentrations in order to infer the possible effects of future climate perturbations on ozone concentrations. Days with elevated ozone concentrations were highly correlated with rainfall (negative correlation) and solar intensity (positive correlation). A weaker positive correlation between temperature and ozone concentrations also was exhibited.

This Project Summary was developed by EPA's Atmospheric Research and Exposure Assessment Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Global atmospheric changes are expected to occur within the next several decades because of increases in levels of pollutants in the atmosphere. These changes are associated with (1) warming of the atmosphere due to the greenhouse effect of trace gases, (2) depletion of the stratospheric ozone layer, and (3) modification of tropospheric chemistry. The emitted materials responsible for those changes are carbon dioxide, carbon monoxide, methane, chlorofluoro-hydro-

carbons, nitrous oxide, and other trace gases.

As atmospheric concentrations of the so-called "greenhouse gases" continue to increase, the potential climate change and consequent environmental impacts have become issues of great concern worldwide. Such climate changes could significantly affect the chemistry and dynamics of the troposphere and ultimately endanger human health and sensitive ecological systems. Of particular concern to many parties, including the Environmental Protection Agency (EPA) and National Park service (NPS), is the possibility that increased temperature and depletion of stratospheric ozone may result in increases in tropospheric concentrations of ozone. The resulting increased reactivity of the troposphere would also result in increased concentrations of other photochemically active species, such as hydrogen peroxide and peroxyacetyl nitrate. Hydrogen peroxide is believed to be one of the principal chemicals in the formation of sulfate and consequently acid deposition, by acting as an oxidizer of sulfur dioxide, while increased concentrations of ozone and peroxyacetyl nitrate may result in significant damage to forest ecosystems.

To provide an initial estimate of the possible effects of future climate changes on tropospheric oxidant concentrations, the EPA, through an interagency agreement with the NPS, funded a preliminary study that examined the effects of future climate changes on urban air quality at several U.S. cities. Specifically, this study used a computer simulation model, OZIPM3, a simple photochemical trajectory box model, to study the effects of increased temperature and decreased stratospheric ozone on ozone formation. The results indicated that, if anticipated climate changes do occur, most of the cities studied will not be able to meet the current National Ambient Air Quality Standard (NAAQS) for ozone (0.12 ppm) without more emission controls than are currently envisioned.

This preliminary study, however, did not estimate the effects of future climate changes on ozone concentrations in the rural atmosphere. The simulation model used in the study, OZIPM3, does not completely simulate the complex interaction between the processes of transport, diffusion, chemistry, and deposition, nor does it include any feedback mechanisms between these processes. In addition, because the model does not divide the atmosphere into more than one vertical layer, it does not properly account for emission, meteorological, and chemistry variations with height, which may be important in both urban and rural environments. Therefore, the purpose of the study reported here was to examine the ability of another model to assess the effects of future climate change on tropospheric air quality. This model, the RTM-III, is an Eulerian three-dimensional regional oxidant model that has been developed over several years.

Procedure

This study involved two tasks. One task was to examine past RTM-III calculations of regional ozone concentrations in order to estimate the sensitivity of the model to changes in climate. Ozone concentrations predicted by the model were related to meteorological input parameters in order to gain insight into how potential future perturbations of these meteorological parameters will affect ozone concentrations. The other task was to determine the sensitivity of the RTM-III to changes in climate by simulating a base case of current climate conditions and potential future climate sensitivity scenarios.

To estimate the sensitivity of past RTM-III calculations of ozone to climatic change, past model simulations were reanalyzed and the meteorological conditions used as input were classified into sets of variables. Measures of these variables were developed through spatial and temporal averaging that would best relate them to ozone concentrations. The predicted ozone concentrations associated with these sets of meteorological conditions were then examined to determine their sensitivity to variations in climatic conditions.

An updated version of the RTM-III was then applied to two modeling domains: one covering central California and the other covering the midwestern and southeastern United States. For each modeling domain the model was exercised for a base case of current temperature and ultraviolet light conditions, and for a future climate scenario reflecting the effects of global warming. The model's ozone concentration predictions were then analyzed to determine the sensitivity of the model's predictions of tropospheric air quality to climate changes.

This study provides a preliminary estimate of the sensitivity of calculations of air quality to climate changes and should help identify those climate parameters to which the calculations are most sensitive. These results will help focus future research on the effects of possible changes in climate on air quality.

Results and Discussion

Application of the RTM-III for Future Climate Scenarios

The continued release of emissions of carbon dioxide (CO_2) and other trace gases has in recent years led to the concern that these trace gases will result in a global warming of the atmosphere by blocking the escape of thermal infrared radiation. This phenomenon is commonly referred to as the greenhouse effect. To quantify the amount of global warming expected in the future, global circulation models (GCMs) and other climate models have been exercised with various estimates of future loadings of trace gases in the upper atmosphere. We analyzed the predictions of climate change from four GCMs to obtain two representative future climate scenarios: a 4°C temperature increase and a combination of a 4°C temperature increase with a 10 percent reduction in stratospheric ozone.

The future climate scenarios were based on results from the following four GCMs: (1) National Center for Atmospheric Research (NCAR) Community Climate Model (CCM) model; (2) National Aeronautics and Space Administration (NASA) Goddard Institute of Space Studies (GISS) model; (3) National Oceanic and Atmospheric Administration (NOAA) General Fluid Dynamics Laboratory (GFDL) model; and (4) Oregon State University (OSU) model.

Current estimates of the emission and retention of man-made CO_2 in the atmosphere indicate a distinct possibility that atmospheric concentrations of CO_2 will double within the next century. Under these conditions, several GCMs predict an increase in the global average surface temperature at sea level of from 1 to 5°C. The above four GCMs models predict that the doubling of CO_2 concentrations would increase the global average temperature in the range of 2 to 5°C. The presence of other trace gases, in addition to CO_2, would increase the global warming further. Although the four GCMs generally agree on the level of increase of global average temperature, they do not agree in their predictions of temperature increases in specific regions, such as California. Studies indicate that current GCMs cannot, as yet, provide meaningful results for specific regions of interest.

Because of these limitations, translating the output of GCMs to hourly average temperature increases for a specific region of interest, as required by a

regional air quality model such as the RTM-III, is problematic. The temporal and spatial scales of a GCM (decades and thousands of kilometers) are not compatible with those of a model like RTM-III (hours and 10 to 50 km). Because of difficulties in adapting the GCM output to a regional model and the discrepancies in the predictions of the GCMs for many climate variables, we have assumed simply that the temperature increases by 4°C throughout the modeling region.

Three modeling scenarios were defined to estimate the effect of future climate changes on tropospheric ozone concentrations: (1) Base case—current meteorological and ozone column conditions; (2) Scenario #1—4°C temperature increase and attendant increase in water vapor concentrations; and (3) Scenario #2—4°C temperature and water vapor increases and a 10 percent reduction in stratospheric ozone concentrations.

The RTM-III was exercised for ozone episodes of approximately one-week duration for the central California and the midwestern/southeastern modeling domains for the base case and scenario #1. Due to limitations on time and resources for this work, scenario #2 was modeled only for four days from the midwestern/southeastern modeling episode.

There are considerable uncertainties associated with assumptions in the modeling. The uncertainties must be kept in mind when interpreting the modeling results. These uncertainties can be roughly divided into three categories: (1) uncertainty in the assumptions used to define the climate change scenarios, (2) uncertainties in the model inputs, and (3) model limitations. The climate change scenarios studied represent a very simplistic description of future climate perturbations. The temperature increase was assumed to occur spatially and temporally constant and independent of other meteorological (except water vapor concentrations) and other variables (e.g., winds, mixing heights, emissions, etc.) that are known to be interdependent. However, the inclusion of these interdependencies would require assumptions that would introduce additional uncertainties and confuse the analysis.

The effect of an increase in temperature tended to increase the predicted maximum daily ozone concentrations immediately downwind of the major urban areas for each of the six days of the central California modeling episode. In more remote areas, such as the Sierra Nevada mountains, the increase in temperature had no effect on the maximum daily ozone concentrations. The peak predicted maximum daily ozone concentration increased from 3 to 20 percent due to the temperature increase.

For the midwestern/southeastern application of the RTM-III, the increase in temperature had less of an effect on the maximum daily ozone concentrations. The maximum increase in the peak daily ozone concentrations due to the increase in temperature was 8 percent. Downwind of the major urban areas (Chicago, Detroit, St. Louis, etc.) ozone concentrations tended to increase due to the increase in temperature, whereas in other areas there was no change and sometimes ozone concentrations decreased.

The effects of increased ultraviolet irradiance or temperature on tropospheric ozone concentrations depends on the oxidant-forming potential of the system. This in turn is generally a function of meteorological conditions and the efficiency of the atmospheric system in converting oxidant precursors to oxidants. For some atmospheric systems the increased energy results in increased reactivity in the morning hours, depleting enough oxidant precursors from the system to limit afternoon ozone production to levels lower than the base case. For climate change scenario #2 (increase in temperature and decrease in the stratospheric ozone column) ozone concentrations tended to be higher or lower than seen in the other scenarios depending on the amount of precursors present. These results are consistent with previous studies that showed that under conditions of increased temperature and UV radiation the highest ozone concentrations were frequently lower in cities with less oxidant precursors. This is because the increased energy, due to an increase in temperature and/or UV radiation, burns out the oxidant precursors earlier in the day, resulting in less oxidant precursors in the afternoon, the period of maximum ozone formation potential. The rather coarse grid spacing used in the midwestern/southeastern modeling domain (approximately 50 km on a side) reduces the peak precursor concentrations from the urban areas because of dilution in the large grid cells.

Although this preliminary model sensitivity analysis may be useful in anticipating the kinds of air quality controls that may be needed in responding to potential global climate changes, the uncertainties associated with predicting just how the climate may be modified preclude any definitive discussion here of regulatory controls. These preliminary modeling results can only indicate possible general trends in exceedances of the ozone standard and increases in the number of people exposed to unhealthy levels of ozone as a result of global climate change.

The study indicates that immediately downwind of urban areas increased temperature tends to (1) increase ozone concentrations, (2) move the location of the peak ozone concentration closer to urban areas, and (3) expand the area in which ozone concentrations exceed the primary ozone standard of 12 pphm. Thus the modeling study indicates that global warming will not only lead to more exceedances of the primary ozone standard over a larger area, but also to an increase in the number of people exposed to these elevated ozone concentrations. Model calculations indicate that approximately three times as many people in the central California modeling domain and 60 percent more people in the midwestern/southeastern modeling domain will be exposed to hourly ozone concentrations in excess of the NAAQS as a result of a 4°C temperature increase. In addition, the modeling results suggest that, with the increase in temperature, people in central California will be exposed to ozone concentrations in excess of 16 pphm whereas under current temperature conditions the modeled ozone concentrations do not exceed 16 pphm.

These results must be viewed with caution. As discussed earlier, numerous simplifying assumptions were made in modeling the impacts of climate change on ozone, and these assumptions add significantly to the quantitative uncertainty normally inherent in air quality modeling. Some of these assumptions, e.g., that the increase in temperature occurs everywhere, will tend to overstate the effects of increased temperature, while others, e.g., that hydrocarbon emissions do not increase under increased temperature conditions, tend to understate the impacts. The climate change scenarios presented here are simplistic and most likely do not completely describe the changes in climate associated with global warming. The model's calculations of ozone under the simplified climate change scenarios discussed here should thus be viewed as possible trends rather than as conclusive impacts. The basic results of this modeling exercise are that increases in temperature will likely result in increases in maximum daily ozone concentrations, increases in the areas impacted by high ozone concentrations, and increases in the number of people exposed to

unhealthy levels of ozone. Under these circumstances, currently planned emission control requirements to achieve attainment of the ozone standard may not be sufficient.

Analysis of Historical RTM-II Simulations to Infer the Effects of Potential Climate Changes on Ozone Concentrations

The analysis of past RTM-III simulations consisted of several steps: (1) Meteorological variables that potentially influence ozone concentrations were selected; (2) Measures of these variables were developed, through spatial and temporal averaging that would best relate them to ozone concentrations; (3) The measures were grouped into climatic types that are associated with ozone concentrations; and (4) The feasibility of using such grouping schemes to predict ozone concentrations was assessed. The following meteorological variables were analyzed: temperature, wind speed and direction, water vapor mixing ratio, mixing height, emission rates, exposure class, precipitation rates, cloud cover, and the radiative flux for photochemical reactions.

A number simple techniques for reducing the thousands of data points available for each day to a dozen or so which have the greatest predictive power for maximum daily ozone concentrations were used: (1) Variables were combined into composite indexes based on a knowledge of chemistry, dispersion, and emissions. For example, wind speed and the mixing height can be multiplied into a product which is sometimes known as the 'ventilation'; (2) Redundant data were eliminated by combining or removing intercorrelated variables and deemphasizing areas where there is no need for representation by a classification variable; (3) Data were systematically averaged in time and space; and (4) Variables were extracted from the model.

The data base for this analysis was developed from three RTM-III simulations: *Eastern US Simulation* (a domain that encompasses nearly all of the eastern United States and a large portion of the Midwest; the modeling period was 15 August to 15 September 1978); *Midwestern/Southeastern US Simulation* (a domain that extends from the Great Plains to just west of the mid-Atlantic seaboard, and from the northern Great Lakes area to central; three episodes were available April 1980, July 1980, and August 1980); *Central California Simulation* (a domain is the smallest of the three, covering an area roughly bounded by the Pacific coast and Sierra Nevada, and the San Francisco Bay Area and Tehachapi Mountains; the six-day episode occurred in August, 1981).

A correlational analysis was performed to investigate relationships between (1) ozone concentration and the meteorological variables and (2) the meteorological variables themselves. The strength of relationships of the former type is a measure of the ability of a variable to predict ozone concentration, while that of the latter type is a measure of the degree of redundancy within a set of variables. In the northeastern region the maximum daily ozone concentration is significantly correlated (95% confidence level) to rainfall, maximum temperature, morning and total daily solar radiation, daily average and afternoon ventilation, and daily average and afternoon wind speed. Most highly correlated are morning and daily total solar radiation ($r = 0.56$ and 0.53, respectively) and rainfall ($r = -0.51$).

In the midwestern episode 1 (April 17-25 1980), the maximum daily ozone is significantly correlated (95% confidence level) with daily average and maximum temperature, daily average and maximum water vapor mixing ratio, and daily total and morning solar radiation. Most highly correlated are daily average temperature ($r = 0.67$) and daily total solar radiation ($r = 0.54$). In the midwestern episode 2 (7-21 July 1980), the relationships between the meteorological variables and maximum daily ozone concentrations are relatively weak. Those significant at the 95% confidence level are daily total solar radiation ($r = 0.37$), afternoon ventilation ($r = -0.30$), and afternoon mixing height ($r = -0.29$). In the midwestern episode 3 (8-18 August 1980), the maximum daily ozone concentration is significantly correlated (at the 95% confidence level) with rainfall, daily average and maximum water vapor mixing ratio, daily average and maximum ventilation, and daily average mixing height. All correlation coefficients were negative and relatively low; none exceeded 0.34 (absolute value).

In the central California episode, no meteorological variables are correlated with maximum daily ozone at the 95% confidence level. This may be due to the small sample size ($N = 12$). The strongest relationship was that of daily average ventilation and ozone, ($r = -0.590$). This is typical for the region, where complex terrain can restrict air flow and produce an ozone episode if wind speeds and mixing heights are low.

Overall, solar radiation appears to have the strongest and most consistent relationship with ozone. One or both measures of solar radiation (morning total daily) were among the top three variables with the strongest relationship with ozone in three out of the five episodes analyzed. However, typically clear skies during the ozone season in California make solar radiation a poor descriptor of ozone. Here the dominant influence on air quality is the interaction of mesoscale air flows with complex terrain; thus, wind speed and ventilation are highly related to ozone in California.

Other variables are occasionally highly related to ozone concentrations; their importance seems to be tied to the magnitude of the variables involved. For example, in the April 1980 midwestern episode, there is a relatively strong positive relationship between temperature and ozone concentration. Temperatures during this episode were much lower than during the other two midwestern episodes, which occurred in summer. The northeastern episode had the second lowest average temperature and was the only other episode in which temperature was significantly correlated with ozone. These results suggest that the lower the temperature, the greater its influence on ozone concentrations.

Rainfall is another example of a variable whose magnitude influences its relationship with ozone. Average and maximum rainfall were highest in the northeastern episode and second highest in the August 1980 midwestern episode; these two episodes also exhibit the strongest and second strongest relationships between rainfall and ozone concentration, respectively. From these results, it appears that if rainfall occurs infrequently and in small amounts, it does little to influence ozone concentrations; conversely, when relatively large amounts of rainfall occur, it has a strong (negative) influence on ozone concentrations.

Conclusions and Recommendations

This study explored the sensitivity of a regional oxidant model, RTM-III, to variations in atmospheric parameters in an effort to establish the usefulness of using a photochemical model to analyze the impact on air quality of global climate changes. The results of the study indicate that the ozone concentrations predicted by a complex model using current atmospheric chemistry are sensitive to the climate change scenarios studied. Within the uncertainties prese the modeling results suggest there could

be potentially significant increases in photochemical pollutants due to future climate changes.

Given the preliminary nature of this study, and its limitations, it is recommended that in future studies the potential air quality impacts of global climate change be examined in more detail. While such details are impossible to completely define because of the exploratory nature of such a study, it is possible to provide an outline of possible recommended approaches.

Include more complex climate change scenarios. In the preliminary study reported here only two meteorological parameters were changed: UV intensity at the surface and atmospheric temperature. A third parameter, atmospheric water vapor, was calculated as function of temperature, assuming that the specific humidity was held constant. Future studies should examine an expanded set of linked meteorological parameters (wind, relative humidity, cloud type and cover, precipitation, etc.) in addition to those used in this preliminary examination.

Consider climatic feedback and consistency in meteorological parameters. If linked parameters are to be considered, it is imperative that climatic feedback be treated in the simulations.

Broaden the range of climate perturbations. To include all variations in climate conditions contained in the GCM scenarios, future studies should include a broader range of meteorological parameters that are varied.

Analyze the impact of global change on the effectiveness of current air quality strategies. The study reported here examined future air quality conditions assuming no change in precursor emissions from today. Current regulatory efforts to reduce ozone concentrations involve reducing emissions of VOCs and NO_x, which could dramatically alter the chemical mix of the atmosphere and possibly the chemical response to potential changes in climate. Future studies should examine the impacts of global climate change on an environment that more closely resembles the one that is likely to result from the implementation of possible control strategies.

Increase the number of regions and meteorological conditions. This preliminary study was severely restricted, by time and resources, to an examination of the climatic sensitivity of a model for two specific ozone episodes in two regions of the U.S. Future studies should increase the number of regions and meteorological scenarios analyzed, thereby permitting somewhat more general conclusions about the impact of global climate change on air quality.

Extend the analysis of input data. The analysis of the input data for past RTM-III applications was both preliminary and incomplete. Other applications of the RTM-III and similar models as their results become available (e.g. ROM, RADM, UAM) should also be analyzed.

Extend the analyses to observed data. The same statistical analysis as applied to the RTM-III predictions could be applied to observed ozone and meteorological data.

Changes in the frequency of ozone exceedances. The data analysis does not address how a change in climate may result in an increase in the number of exceedances of the ozone air quality standard. A methodology should be developed that will relate changes in meteorological parameters to changes in the observed frequency of ozone exceedances with some estimate of the uncertainty included.