7.11 The Effect of Future Anthropogenic Emissions on Ozone Concentrations in the Great Lakes Region

Jerome D. Fast[1] and Warren E. Heilman[2]
[1]Pacific Northwest National Laboratory, Richland, Washington
[2]USDA Forest Service, East Lansing, Michigan

1. Introduction

In addition to the effects of ozone on human health, high surface ozone concentrations can have an adverse effect on specific types of vegetation in the Great Lakes region. Ozone exposure estimates have typically been based on ozone monitoring data or empirical techniques that also include other information such as meteorological conditions, emission rates, and distance from emission sources (Hogsett et al. 1997).

Global and regional-scale climate predictions indicate human activities will significantly alter the average meteorological conditions over the next several decades (IPCC, 2001). Future vegetation health will depend on the interaction of changes in meteorological parameters and pollutant emission rates that influence air quality and ozone exposure.

In this study, a coupled meteorological and chemical modeling system, PEGASUS, was used to simulate the production/destruction, turbulent mixing, transport, and deposition of ozone over the western Great Lakes region during the summer of 1999 and 2001. These two years were chosen because of contrasting meteorological conditions. The synoptic conditions during the summer of 1999 were favorable for ozone production in the region, while the summer of 2001 was cooler and wetter and lower ozone concentrations were observed. Additional simulations were performed to examine the effect of projected anthropogenic trace gas emission rates on ozone exposure and how sensitive the predicted changes in ozone concentrations are to the different meteorological conditions between these two summer seasons.

2. Model Description

PEGASUS (Fast et al. 2002) is a one-way coupling of a mesoscale meteorological model and a chemical transport model. Two nested grids were employed: an outer domain that included most of eastern North America with a grid spacing of 36 km and an inner domain that encompassed the western Great Lake region with a grid spacing of 12 km. Fifty grid points were used for the vertical coordinate, with a grid spacing of 25 m adjacent to the surface that gradually increased to 750 m near the model top at 20 km. Due to the staggered vertical coordinate, the first grid point was 12.5 m AGL.

A five-month simulation period between 1 May and 30 September was chosen to simulate ozone evolution during the late spring and throughout the summer.

**Corresponding author address:* Jerome D. Fast, Pacific Northwest National Laboratory, P.O. Box 999, K9-30, Richland, WA 99352, e-mail:jerome.fast@pnl.gov

2.1 *Meteorological model*

The turbulence parameterization in the mesoscale model consists of a simplified second-order closure method that employs a prognostic turbulence kinetic energy equation. A cumulus parameterization and microphysics were used to predict cloud amount and precipitation.

The initial and lateral boundary conditions for the meteorological simulation were based on the National Center for Environmental Prediction's AVN model analyses at 6-h intervals. To limit forecast errors in the synoptic conditions over the five-month period, four-dimensional data assimilation was applied that nudged the simulated winds, temperature, and humidity to the AVN model analyses. Lake temperatures on the inner nested grid varied linearly in time based on the NOAA Great Lakes Environmental Research Laboratory daily 3-km analyses derived from satellite data.

2.2 *Chemical transport model*

Hourly fields of horizontal and vertical wind components, temperature, humidity, eddy diffusivity, cloud parameters, and surface properties were obtained from the mesoscale model. The cloud parameters are used to influence large-scale vertical mixing and photolysis rates. Boundary conditions for the trace gas species on the outer grid were set to constant background values. Ozone and ozone precursors produced over the outer grid are used as time varying boundary conditions for the inner grid.

Hourly emission rates of 14 species were obtained from the Sparse Matrix Operator Kernel Emissions (SMOKE) model (Houyoux et al. 2000). The SMOKE emissions were generated off-line on a 4-km grid over the eastern U.S. and Canada. The emissions were then aggregated to the 36 and 12-km grid cells used by the two nested grids. Emissions were vertically resolved by SMOKE for the lowest 8 layers of the domain. Emissions above the first layer are primarily from point sources, such as those from power plant stacks. As expected, the highest ozone precursors emission rates occur over urban areas. A few point sources with high emission rates are located in rural areas along the shores of Lake Superior and Lake Huron.

2.3 *Experimental design*

Two sets of simulations are performed: "control simulations" and "emission projection simulations". The control simulations are designed to reproduce, as best as possible, the evolution of the observed spatial distribution and magnitude of ozone in the Great Lakes region throughout the 1999 and 2001 summer seasons.

Predicted ozone exposure is evaluated with the available observations. We assume that the model produces realistic estimates of ozone exposure in remote regions, where there are no observations, when the simulated ozone exposure is consistent with measurements in other parts of the domain. The emission projection simulations are identical to the control simulations, except that the anthropogenic emission rates were modified by emission factors obtained from EPA's Economic Growth Analysis System (EGAS) for the year 2020 (http://www.epa.gov/ttn/chief/emch/projection/egas40).

3. Results

The simulated winds, temperatures, and humidity from the mesoscale model have been compared with hourly surface meteorological stations and twice-daily upper air soundings (not shown). The simulated winds followed the observed synoptic patterns during the five month period as expected because the model used four-dimensional data assimilation.

We briefly describe here a sample of the main findings of the predicted ozone exposure. A description of the synoptic meteorological conditions and a statistical evaluation of the predicted meteorological quantities and ozone concentrations will be presented at the conference.

3.1 *Control simulations*

Time series of predicted ozone over the summer periods were compared with the available EPA surface monitoring data. An example of the observed and predicted ozone at Ann Arbor, Michigan for June of 1999 and 2001 is shown in Fig. 1. The model qualitatively reproduces the diurnal and multi-day variation in ozone. Predictions from PEGASUS, as with all air quality models, are not perfect and there are periods where the model over-predicted (e.g. 3–7 June, 2001) or under-predicted (e.g. 7–8 June, 1999) the afternoon peak ozone concentrations. The differences between the observed and simulated ozone concentrations for the other months are similar to those shown in Fig. 1.

The ozone exposure between May and September each year was computed for ozone mixing ratios greater than 60 and 80 ppb. The results for ozone exposure greater than 80 ppb are shown in Fig. 2. PEGASUS reproduced the overall spatial distribution and magnitude of ozone exposure. The highest observed ozone exposure occurred at a few monitoring stations located along the eastern shore of Lake Michigan. The model also produced high values over the much of the lake surface. High ozone mixing ratios were frequently produced over the lake because the shallow marine stable boundary layer trapped pollutants advected over the lake, primarily those from Milwaukee and Chicago emission sources. The reduced vertical mixing in the marine boundary layer lead to high ozone production rates, as described in Fast and Heilman (2003). Except for a few point sources, the emission rates of ozone precursors are low in the remote regions surrounding the Great Lakes in the northern third of the domain. The ozone exposure in these areas was produced by northerly transport of ozone.

The model also produced higher ozone exposure during 1999 than during 2001, consistent with the observations. The overall pattern of ozone exposure between the two years was similar, except that the predicted ozone mixing ratios north of Lake Superior were always less than 80 ppb during the summer of 2001.

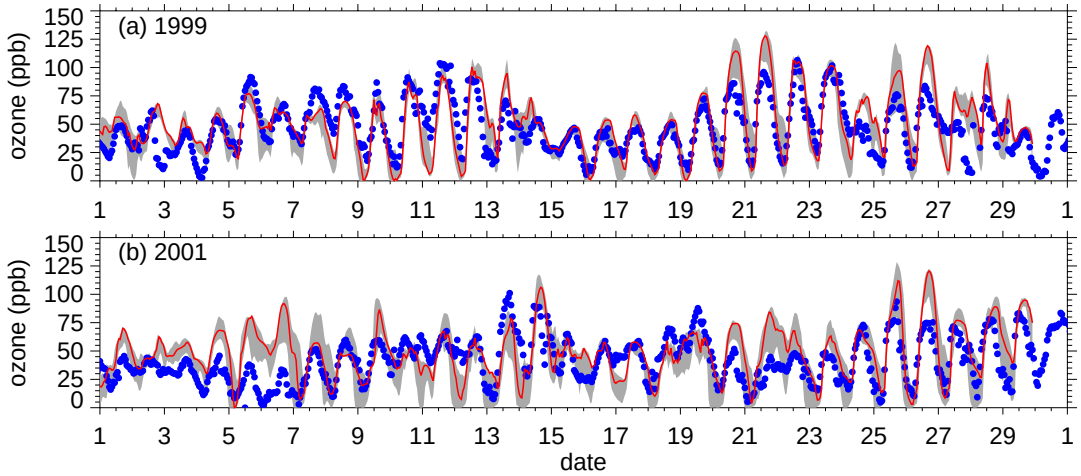

Fig. 1. Observed (dots) and predicted (line) ozone at Ann Arbor, Michigan during June of (a) 1999 and (b) 2001. Gray shading denotes range of simulated ozone for the grid points within 12 km of Ann Arbor.

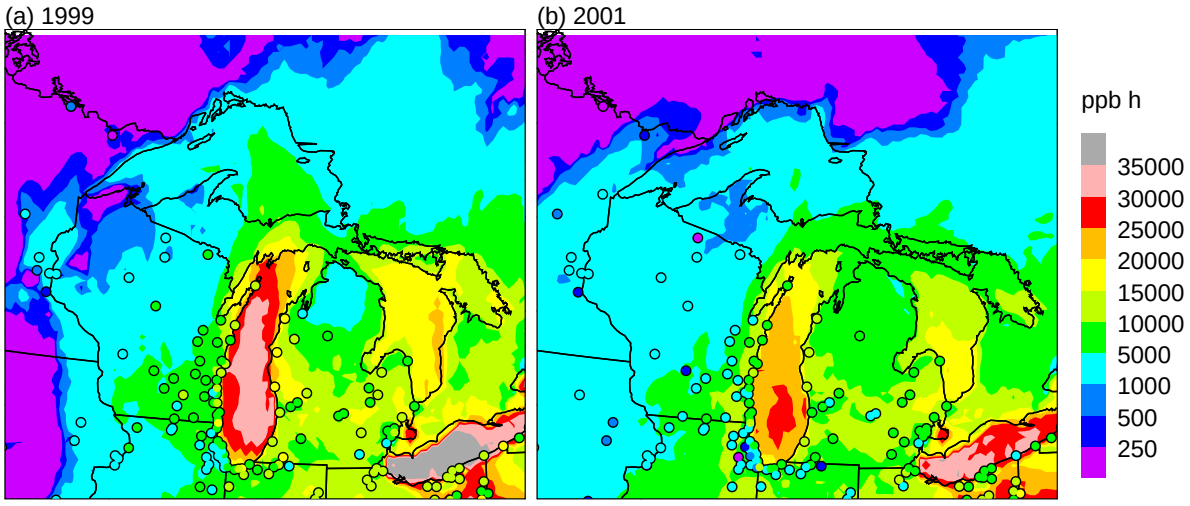

Fig. 2. Observed (dots) and simulated (contours) ozone exposure (> 80 ppb) between May and September of (a) 1999 and (b) 2001.

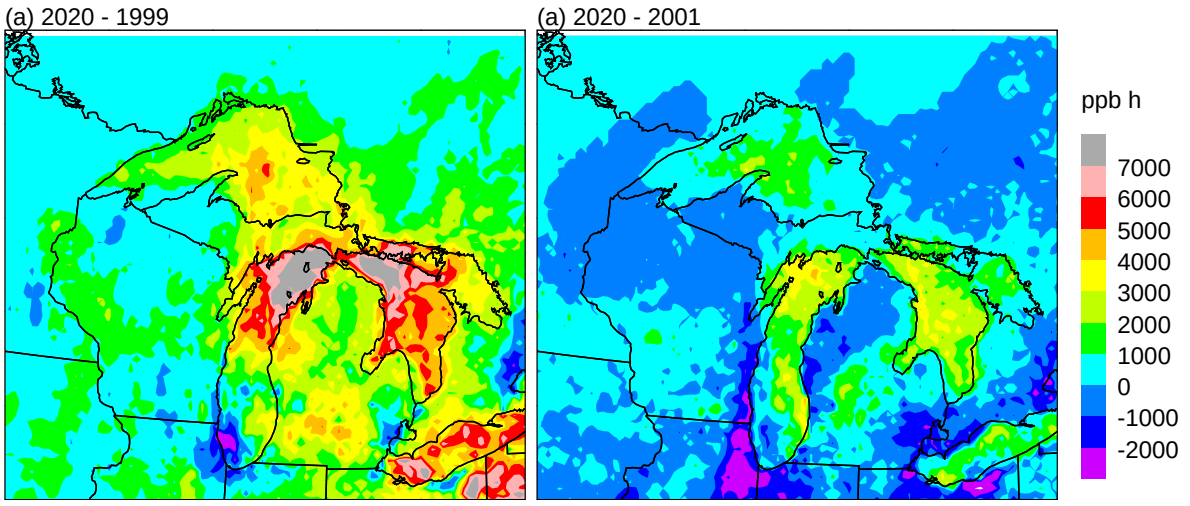

Fig. 3. Ozone exposure difference between 2020 emission projection simulations and control simulations for meteorology during the summer of (a) 1999 and (b) 2001.

3.2 *Emission projection simulations*

Because the model was able to reproduce the overall meteorological conditions and ozone distributions during the two summer periods, we also used the model to investigate the effect of projected emission rates (for the year 2020) on ozone production and overall ozone exposure during the two summer seasons.

The resulting difference in ozone exposure between the emission projection and control simulations are shown in Fig. 3. For the simulation that employed the meteorological conditions during 1999, the changes in anthropogenic emissions increased nitrogen oxide (NO) titration, that in turn, reduced ozone levels in the immediate vicinity the large metropolitan areas of Chicago, Milwaukee, Detroit, and Cleveland. Higher levels of nitrogen oxide emissions, however, also increased ozone production downwind of the emission sources. A significant increase in ozone exposure was predicted over most of Michigan and downwind over the northern Great Lakes region. In contrast, a modest increase in ozone exposure was predicted in isolated areas by the simulation that employed the 2001 meteorological conditions that were less favorable for ozone production.

These results suggest that changes in future air quality will depend significantly on the meteorological conditions and that predictions of future air quality will require an understanding of how climate change can affect average synoptic conditions in the region. Increased frequency of high pressure systems with clear skies will be favorable for more ozone production, while increases in low pressures systems will lower ozone production because of increased cloudiness and and lower photochemical production. Another important factor in predicting future air quality is the magnitude

and spatial distribution of projected emission rates. Projections of anthropogenic emissions rates of ozone precursors are highly uncertain because they depend on assumptions of population, economic development, land-use patterns, and technology.

Acknowledgments. This research was supported by the USDA Forest Service under Interagency Agreement # 02-IA-11231300-047. The Pacific Northwest National Laboratory is operated for the DOE by Battelle Memorial Institute under contract DE-AC06-766RLO 1830.

4. References

Fast, J.D., and W.E. Heilman, 2003: The effect of lake temperatures and emissions on ozone exposure in the western Great Lake region. *J. Appl. Meteor*., 42, 1197-1217l

Fast, J.D., R.A. Zaveri, X. Bian, E.G. Chapman, and R.C. Easter, 2002: The effect of regional-scale transport on oxidants in the vicinity of Philadelphia during the 1999 NE-OPS field campaign. *J. Geophys. Res*., 107, 10.1029/2001JD000980.

Hogsett, W.E., J.E. Weber, D. Tingey, A.Herstrom, E.H. Lee, and J.A. Laurence, 1997: Environmental Auditing: An approach for characterizing tropospheric ozone risk to forests. *Environ. Management.*, 21, 105-120.

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

Intergovernmental Panel on Climate Change, 2001: Climate change 2001: The scientific basis. www.grida.no/climate/ipcc_tar/.

.