Observed relationships of ozone air pollution with temperature and emissions

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[1] Higher temperatures caused by increasing greenhouse gas concentrations are predicted to exacerbate photochemical smog if precursor emissions remain constant. We perform a statistical analysis of 21 years of ozone and temperature observations across the rural eastern U.S. The climate penalty factor is defined as the slope of the ozone/temperature relationship. For two precursor emission regimes, before and after 2002, the climate penalty factor was consistent across the distribution of ozone observations. Prior to 2002, ozone increased by an average of ~3.2 ppbv/°C. After 2002, power plant NOx emissions were reduced by 43%, ozone levels fell ~10%, and the climate penalty factor dropped to ~2.2 ppbv/°C. NOx controls are effective for reducing photochemical smog and might lessen the severity of projected climate change penalties. Air quality models should be evaluated against these observations, and the climate penalty factor metric may be useful for evaluating the response of ozone to climate change. Citation: Bloomer, B. J., J. W. Stehr, C. A. Piety, R. J. Salawitch, and R. R. Dickerson (2009), Observed relationships of ozone air pollution with temperature and emissions, Geophys. Res. Lett., 36, L09803, doi:10.1029/2009GL037308.

1. Introduction

[2] Power plant NOx emissions decreased by 43% for the time period 1995 to 2002 compared with 2003 to 2006 as a result of air pollution control programs in the eastern United States [Kim et al., 2006; Bloomer, 2008]. Emissions from automobiles and industrial activity have essentially remained constant, as indicated from satellite observations of tropospheric NO2 [Kim et al., 2006]. Early indications from ambient monitoring networks and atmospheric chemical transport models provide evidence that ozone amounts have declined as a result of fallen power plant emission [Gégó et al., 2007, 2008].

[3] Temperature can be used as a surrogate for the meteorological factors influencing surface ozone formation [Jacob et al., 1993; Ryan et al., 1998; Camalier et al., 2007]. Temperature has been rising, on average, in the eastern U.S. [Intergovernmental Panel on Climate Change (IPCC), 2007]. Surface ozone is expected to rise, all else being equal, with an increase in temperature [Environmental Protection Agency, 2006]. The ozone temperature relation-

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2. Measurements and Statistical Method

2.1. NOx Emissions

[7] NOx emissions from power plants were historically estimated from fuel sampling and analysis methods. Since 1995, continuous emission monitoring equipment has been operating in the exhaust gas stream of the largest fossil fuel fired plants nationwide. Care must be used in assessing NOx emission from power plants when combining data sources and when using emissions numbers from government databases. We have analyzed the historical trend of ozone season (1 May to 30 September) NOx emission from power plants and conclude two distinct emission regimes can be constructed [see also Bloomer, 2008].
with over 3 million simultaneously valid observations of temperature and ozone across the eastern U.S. For example, the resulting data set for the Mid-Atlantic region includes 1,196,350 individual valid observations of concurrent temperature and ozone, with 343,398 observations after 2002, and 852,952 from 1987 up to and including 2002 [Bloomer, 2008].

[11] We used the exploratory data analysis techniques described by Wilks [2006]. In general, parametric tests rely on strict assumptions about the probability distribution of the data, such as assuming the distribution is Gaussian. In our study, we do not make these assumptions because more general and conservative conclusions are possible. The shapes of the full ozone and temperature distributions have little documentation in the literature. Non-parametric methods are more robust and resistant to influence from outliers due to instrument error or anomalous conditions. Further details are given in the auxiliary material.1

3. Results and Discussion

[12] The hourly ozone concentrations (including nighttime observations) dropped post-2002 by about 10% in the Mid-Atlantic and Northeast regions across the full distribution (Figure 2). Ozone in the Great Lakes and Southwest regions decreased by larger relative amounts in the upper and lower percentiles. A similar reduction is seen in the subset of observations made during daytime hours. Sampling the daily maxima for 1-hour and 8-hour averages (time periods of interest due to their specification by EPA in the National Ambient Air Quality Standards for ozone) shows large decreases at all locations in the distribution. The largest decreases in ozone occur at the highest concentrations. Ozone in the 95th percentile of the 8-hour average daily maxima in the Mid-Atlantic declined 15.6 ppbv after 2002. This observational evidence supports conclusions previously reported from modeling studies [Geço et al., 2007, 2008].

[13] The ozone concentration (Figure 2) shows decreases across the entire distribution of observed values, pre- to post-2002, for all regions. Figure 2 shows the amount of ozone at each location statistic of the 5th, 25th, 50th, 75th and 95th percentiles occurring prior to and including 2002 (horizontal placement) as well as the change in ozone for each percentile (vertical extent).

[14] Temperature distributions (Figure 2) show that air warmed across the Great Lakes and Mid-Atlantic regions after 2002. Mid-Atlantic temperatures increased the most, especially over the lower portion of the distribution. The median temperature differences are 0.51°C for pre to post-2002 and 0.68°C pre-1999 to post-2002. These are consistent with published estimates of 0.25 to 0.30°C/decade for observed temperature trends for similarly defined regions of the eastern U.S. [IPCC, 2007]. The Mid-Atlantic region has temperature differences larger than those predicted from a global greenhouse gas forcing alone [IPCC, 2007], indicating a regional source of warming due to factors that may not be represented in current global modeling simulations.

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1Auxiliary materials are available in the HTML. doi:10.1029/2009GL037308.
To investigate further the observational data for a relationship between ozone and temperature, we construct conditional ozone distributions corresponding to specific temperature ranges (Figure 3). For all regions, at all times, in any location within the distribution, ozone concentrations increase with increasing temperatures. The spread in the data as a function of temperature shows how other variables influence ozone at a given temperature. This relationship between the location statistics (e.g., the 50th or 75th percentile values) and temperature reveals a consistently strong dependence of ozone on temperature, regardless of where the distribution is sampled. This approach differs distinctly from filtering the observations by choosing daily maximum 1-hr or 8-hr averages prior to examining the ozone vs. temperature relationship. The strength of the temperature relationship is reinforced by the consistency across the percentiles and the relative insensitivity of the relation to temperature bin size [see also Bloomer, 2008]. Our conclusions are insensitive to the precise choice of year to delineate emission regimes, reflecting the transition period for emission reductions between 1998 and 2002 (see auxiliary material).

The ozone-temperature relationship is linear in all four regions before and after 2002 over the temperature range of 19 to 37°C. A linear fit of ozone vs. temperature yields nearly the same slope, regardless of which percentile is chosen for the Great Lakes, Northeast, and Mid-Atlantic regions (Figure 3). The average of the slopes of the five linear fits in the Mid-Atlantic region for data collected prior to 2002, corresponding to the 5th, 25th, 50th, 75th and 95th percentiles, is 3.3 ppbv O_3/°C, with a minimum of 3.2 and a maximum of 3.5 ppbv O_3/°C. The slope decreases to an average of 2.2 ppbv O_3/°C after 2002, with a similarly small range of 1.9 to 2.6 ppbv O_3/°C. The post-2002 data show less ozone compared to the pre-2002 data at higher temperatures, indicating ozone production became less sensitive to temperature increases after the 2002 emission reductions.

We define the climate penalty factor as the slope of ozone versus temperature. This factor, combined with projections of temperature provides an estimate of how air quality may respond to future warming. Essentially, we are using the variability of the natural system (“today’s atmosphere”) to quantify the empirical relation between ozone and temperature and are suggesting this relation serves as a starting point for how the future atmosphere will behave. The climate penalty factor is remarkably similar across the Great Lakes, Northeast and Mid-Atlantic regions, with an
average value for the three regions of 3.2 ppbv $O_3/C^*$C (range: 3.0 to 3.6 ppbv $O_3/C^*$C) prior to 2002 and 2.2 ppbv $O_3/C^*$C (range: 2.0 to 2.5 ppbv $O_3/C^*$C) after 2002. If the analysis is restricted to data collected only during the daylight hours of 10:00 am to 7 pm local time, smaller values are obtained for the CPF, because the data are restricted to a narrower range of ozone values. However, the daylight-only data show a decline in CPF after 2002 similar in magnitude to that found when all data are considered. Table S1 of the auxiliary material illustrates the sensitivity of CPF to time of day. Applying the CPF reported here to other geographic regions or future climatic conditions requires theoretical development and/or proper analysis of model calculations. Nonetheless, proper representation of this CPF for contemporary conditions may serve as an important test for models used to project future air quality.

[18] In the Southwest region ozone decreased after 2002, but the climate penalty factor remained nearly the same. Ozone production in the Southwest region differs from the other regions of our study in that petrochemical and vehicular emissions dominate; the air is rich in highly reactive hydrocarbons. Advection from power plants may play a smaller role, but observations are relatively sparse and results are less robust. The Southwest region shows a small increase in the climate penalty factor after 2002, with values going from 1.3 ppbv/$C^*$C (range: 1.1 to 1.5 ppbv/$C^*$C) before 2002 to 1.4 ppbv/$C^*$C (range: 1.1 to 1.9 ppbv/$C^*$C) after 2002 (Figure 3).

[19] The decrease in ozone concentration and decline in the climate penalty factor observed for the Mid-Atlantic, Great Lakes and Northeast regions after 2002 are statistically significant. Both parametric and non-parametric techniques were applied for determining the significance of the differences in ozone, temperature, and the climate penalty factor as discussed above. Distributions of ozone and temperature were compared to parameterized distributions. The distributions are normal in the middle quartiles, departing significantly from normal at higher ozone values; therefore, we opted to use non-parametric techniques for robust results. Wilcoxon-Mann-Whitney hypothesis testing was performed, and all differences discussed above are highly significant; the probability of falsely rejecting the null hypothesis of no difference is less than 0.001.

[20] This level of significance was observed for the vast majority of the data. For example, in the Mid-Atlantic figure...
region, over 950,000 observations, or more than 80% of the total data, fall between 15 and 37°C. The significance of the difference in ozone and the climate penalty factor broke down only for the highest temperatures of greater than 37°C. These observations represent less than 100 data points, a small fraction of the total. Given the known temporal autocorrelation that exists on the scale of hours to days in the data, we opted to develop additional robust and resistant non-parametric estimates of the standard error for the location statistics, and used these estimates to determine significance as well. We have consistently tended toward overestimating the standard error in our statistical analyses, which provides for great confidence in the statistical significance (meaning differences larger than the combined standard error in this case) of the changes in ozone, temperature, and the climate penalty factor for the Mid-Atlantic, Great Lakes, and Northeast regions. Further details of the statistical significance are given in the auxiliary material.

4. Concluding Remarks

[21] Our analysis indicates that the climate change penalty in air quality decreases when ozone precursor emissions are reduced, as suggested by modeling studies [e.g., Wu et al., 2008]. The slope of the ozone temperature relationship, sampled at the various location statistics of the full distribution, was 3.2 ppbv O3/C (range: 3.0 to 3.6 ppbv O3/C) prior to 2002 and decreased to 2.2 ppbv O3/C (range: 2.0 to 2.5 ppbv O3/C) after 2002, coincident with the 43% reduction in power plant emission of NOx. Assuming that NOx emissions continue to fall, ground level ozone and the climate penalty factor in the eastern U.S. should continue to improve. In regions of increasing NOx emissions, including much of the developing world [Richter et al., 2005], ozone will increase more than expected (based upon emissions alone) if temperatures also rise. Predicted rising temperatures [IPCC, 2007] bode ill for air quality and human health [NRC, 2008; West et al., 2006], unless substantial NOx emission reductions are implemented. The climate penalty factor is of significant concern to affected populations and should be evaluated for more regions of the globe. The climate penalty factor can be combined with estimates of future temperature increases to quantify possible impacts of warming on air quality. The climate penalty factor provides a means for assessing the ozone/temperature relationship of air quality models for present day conditions. Proper representation of this relationship would provide confidence in the accuracy of simulations of the impacts of climate change on future air quality.

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