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Trends in Visibility, PM_{2.5}, and Deposition Expected from the Acid Rain Provisions of the 1990 Clean Air Act Amendments

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ABSTRACT

The Acid Rain Provisions (Title IV) of the 1990 Clean Air Act Amendments (CAAA) are designed to reduce the deposition of SO₂ and sulfate and, to a lesser extent, the deposition of NO_x and nitrate through reduction of SO₂ and NO_x emissions. However, other important benefits are anticipated from the emission control strategies, including improvement of regional visibility and reductions in concentrations of fine particles (PM_{2.5}). In this study, we coupled utility emissions forecasts with the Advanced Statistical Trajectory Regional Air Pollution (ASTRAP) model and the Visibility Assessment Scoping Model (VASM) to calculate and compare the relative improvements by 2010 in visual impairment, PM_{2.5} concentrations, and sulfate wet deposition at selected sites in the eastern United States.

INTRODUCTION

The Acid Rain Provisions of the 1990 Clean Air Act Amendments were designed to decrease acidic deposition through a strategy of reducing emissions of SO₂ and, to a lesser extent, emissions of NO_x, with emissions reductions scheduled to be implemented in 1995-2010. Phase I of the mandated SO₂ emissions reductions became effective in 1995. Preliminary analysis of regional trends in monitoring data for precipitation chemistry and regionally weighted precursor emissions in 1980-1995 indicated that precipitation-weighted concentrations (PWCs) of sulfate have been reduced significantly (Shannon, 1997); somewhat surprisingly, the reductions in regional sulfate PWCs seem to have been greater than the reductions in SO₂ emissions.

Additional air quality benefits should result from the emissions reductions, particularly decreased atmospheric concentrations of particles less than 2.5 microns in diameter (PM_{2.5}), as well as improved regional visibility, or reduced haziness, through lessening of optical extinction from particle scattering. Predicting the signs of the expected changes in deposition, PM_{2.5} loading, and visibility is simple enough; estimating the magnitudes of the changes, particularly expected future changes, requires modeling.

APPROACH

For this analysis, we are using the interim SO₂ emissions projections in the Tracking and Analysis Framework (TAF) integrated assessment (Henrion et al., 1997). The emissions module at the most recent TAF update did not yet include Canadian emissions projections nor projections of non-utility U.S. emissions, but the module included a forecast increase in electricity demand of 1% per year and a plant retirement age of 60 years. The combination of these factors probably leads to underestimation of the SO₂ emissions reduction that will occur between 1990 and 2010; the reduction in annual SO₂ emissions for the 31 eastern states in the emissions projection is 6.5 tg, or about 71% of the "10 million ton" figure frequently mentioned in regard to the 1990 CAAA.

For our studies assessing some air quality benefits of the Acid Rain Provisions, we used the Advanced Statistical Trajectory Regional Air Pollution (ASTRAP) model to simulate regional concentrations, deposition, and source-receptor relationships (Shannon, 1985, 1996) and the Visibility Assessment Scoping Model (VASM) to forecast visual impairment (Shannon et al., 1997). Briefly, ASTRAP produces seasonal mean two-dimensional horizontal trajectories and wet deposition patterns for a grid of virtual sources covering the region of emission interest, with the trajectories produced from ensemble statistics of individual trajectories calculated at 6-h intervals. The individual trajectories are calculated by using wind and precipitation fields over North America updated several times per day, and wet removal is

a function of the half-power of the precipitation amount. In separate calculations, ASTRAP produces seasonal mean one-dimensional vertical profiles of concentration, plus dry deposition and loss to the free troposphere, for pollutants as a function of effective emission height. The numerical integration uses highly parameterized seasonal and diurnal patterns of dry deposition velocity, vertical stability profile, and linear chemical transformation (e.g., SO₂ to sulfate). The trajectory and vertical integration statistics are combined with the appropriate seasonal emission inventory, gridded horizontally and vertically, to simulate seasonal mean surface concentrations and deposition totals.

VASM applies Monte Carlo techniques to produce seasonal distributions of daily or hourly visual impairment. The Monte Carlo techniques combine statistics from the Interagency Monitoring of Protected Visual Environments, or IMPROVE network (Malm et al., 1994), of seasonal geometric means and standard deviations of daily concentrations of fine-particle species (sulfate, nitrate, elemental carbon, organic carbon, and dust) and coarse-particle dust, interspecies concentration correlations, relative humidity (RH) climatology, and modeled future concentrations of one or more of the particle species (here only sulfate). Species not modeled are assumed to maintain their current concentration characteristics. The regional model results are applied in VASM in a relative manner; that is, if the model simulations indicate that future concentrations will be 65% of the model simulations for the current emission inventory, the current observed mean is scaled by 65% for future visibility simulations. The sets of short-term concentrations and RH values generated by the Monte Carlo techniques are then applied in optical extinction functions that vary with the concentration of the particle species and RH (for the hygroscopic species such as sulfate) to produce optical extinction calculations that can be combined with Rayleigh scattering and absorption by NO₂ to produce seasonal distributions of total extinction, b_{ext} , which can be converted to visual-range or deciview distributions.

In our modeling of trends for both PM_{2.5} concentrations and visibility, we are assuming that the expected seasonal means and daily variability of the PM_{2.5} species other than sulfate are unchanged. Recent U.S. Environmental Protection Agency regulatory actions for control of ozone and PM_{2.5} are likely to affect precursor emissions of other particle species, but it is too early to quantify the effects of the rule changes for this preliminary analysis. Because the NO_x emission reductions for ozone control may ultimately dominate the NO_x reductions mandated in the Acid Rain Provisions, this analysis focuses on the air quality effects of the reductions in emissions of SO₂.

The typical contribution of sulfate particles to regional fine-particle concentrations in the eastern United States, as reflected in measurements in the IMPROVE network (Malm et al., 1994) ranges from about 40% in winter to almost 60% in summer, averaging about 50% overall. In urban areas, regional sulfate has less importance because of the increased concentrations of the other particle species. To some extent, the estimated contribution depends on what is assumed about the sulfate speciation (the proportions of ammonium sulfate, ammonium bisulfate, or sulfuric acid); here we have assumed that eastern sulfate is near neutral (predominantly ammonium sulfate) in winter, acidic (predominantly ammonium bisulfate) in summer, and partially acidic in the transition seasons.

Other factors besides the emissions projections applied can bias our results. The ASTRAP model tends to overpredict sulfate concentrations in mountainous terrain during winter and, to a lesser extent, during spring, because the model is not sensitive to terrain and elevated sites are frequently above the regional mixed layer in the cooler portion of the year (Shannon et al., 1997). Because ASTRAP is a linear model, it would be expected to overpredict the improvement (reduction) in sulfate concentrations at those locations and seasons. The model bias would affect only PM_{2.5}, because only relative model results are used in visibility simulations. A factor that might lead to overestimation of the improvement in both fine-particle concentrations and visibility due to SO₂ emissions reductions is that with lower ambient sulfate concentrations, the portion of ambient nitrate in the form of fine-particle ammonium nitrate, rather than nitric acid vapor, may increase because of the reduced competition for neutralization by ammonium.

RESULTS

We examined the visual improvements resulting from the emission reductions at three representative scenic eastern sites (Great Smoky Mountains National Park in Tennessee and North Carolina, Shenandoah National Park in Virginia, and the Green Mountains of Vermont) plus the urban area of Washington, D.C. (Figs. 1a-b). We also assessed the improvement in $PM_{2.5}$ concentrations associated solely with changes in sulfate at those locations (Figs. 2a-b). The receptor locations were selected on the basis of the availability of relevant monitoring data and also because in most cases they are considered sensitive locations. We assessed the improvement in wet deposition of sulfate with modeled values of the average value integrated across the states of New York, Maine, Minnesota, and Ohio (Figs. 3a-b).

Our results indicate that the most pronounced benefit of the emissions reductions should be a decrease in wet sulfate deposition of 20 to 40%. The modeled reductions are relatively greater in New York and Maine, which are usually downwind of the primary area of emissions reductions (the Ohio Valley), than in Minnesota, which is downwind of the Ohio Valley less frequently. Reductions in dry deposition of sulfur (not shown) would be greatest in the primary emissions area, represented by Ohio. The expected relative improvements in visual range (10 to 20%) and $PM_{2.5}$ (15 to 20%) are less than those for sulfate deposition, even though the ASTRAP model is linear for both concentrations and deposition, because other anthropogenic and natural particle species unaffected by the SO_2 emissions changes also contribute to $PM_{2.5}$ concentrations.

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Figure 1a: Modeled seasonal mean visual range

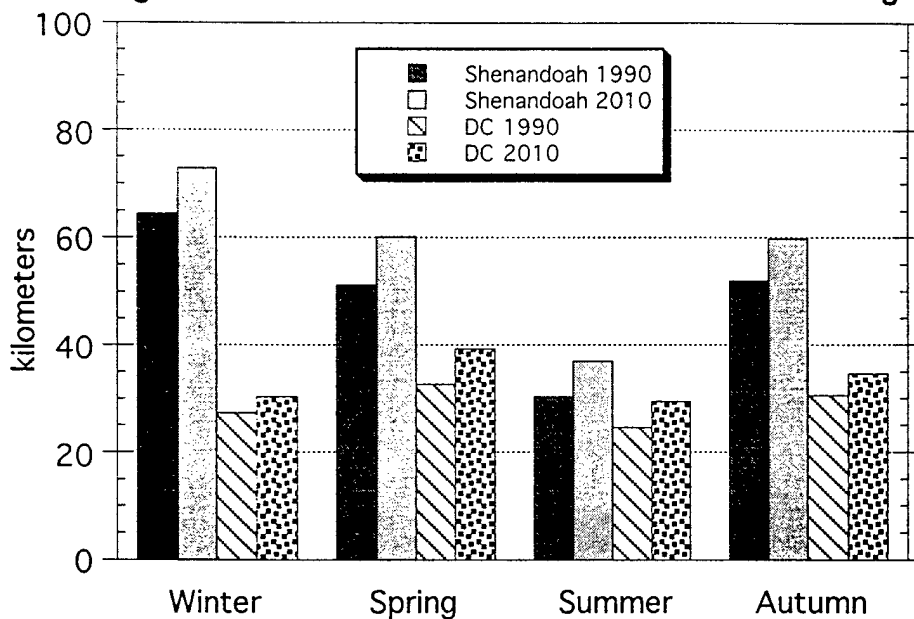


Figure 1b: Modeled seasonal mean visual range

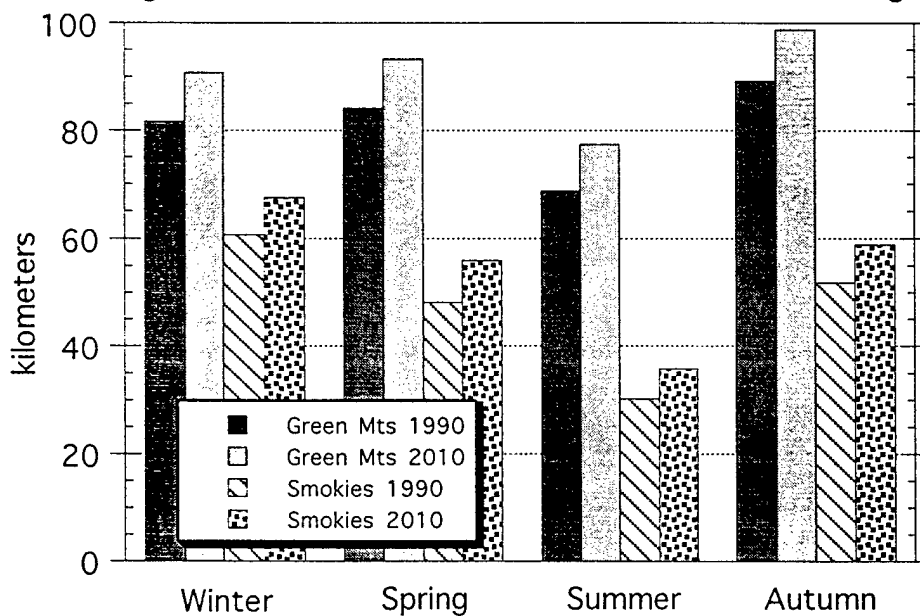


Figure 2a: Modeled seasonal mean PM_{2.5} concentrations

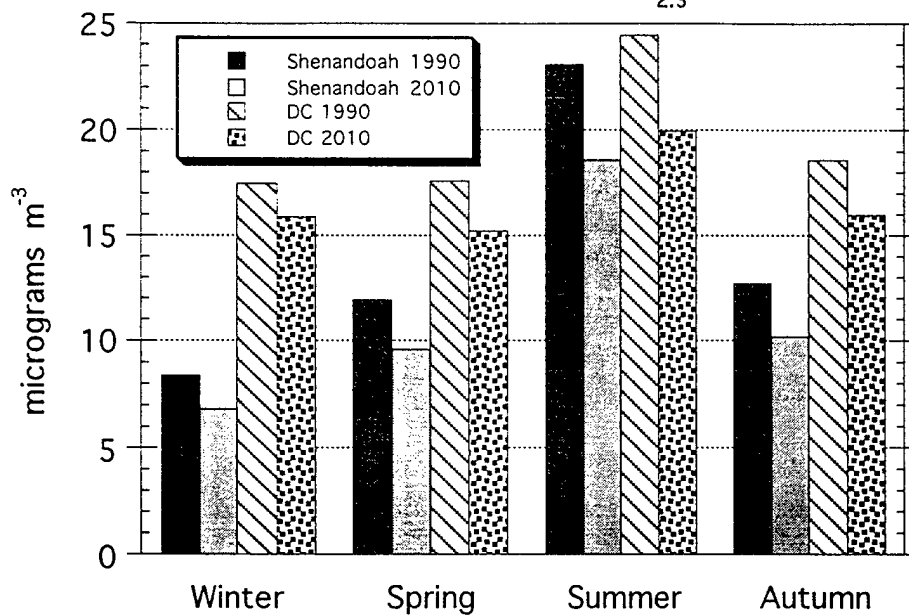


Figure 2b: Modeled seasonal mean PM_{2.5} concentrations

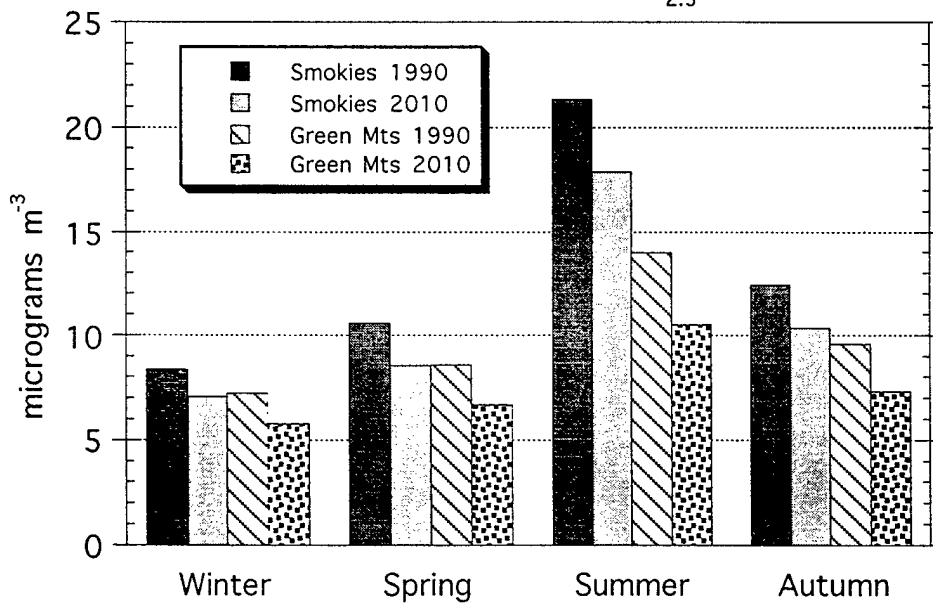


Figure 3a: Modeled statewide average seasonal wet deposition of sulfate from anthropogenic sources

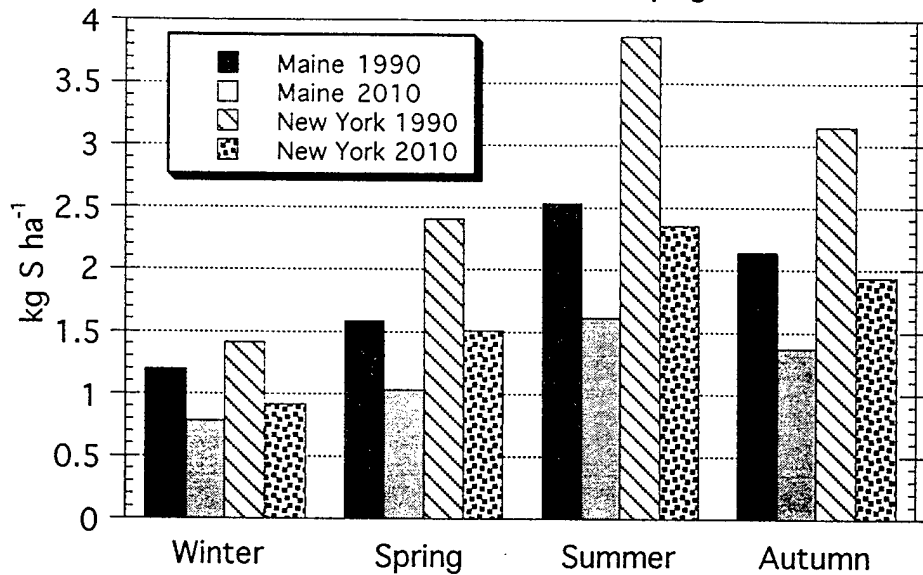
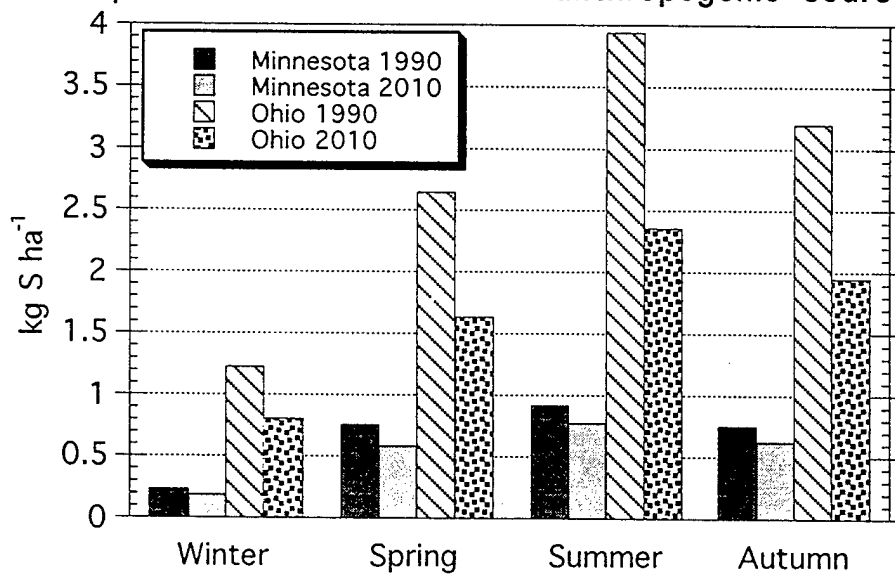


Figure 3b: Modeled statewide average seasonal wet deposition of sulfate from anthropogenic sources



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