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EFFECTS OF THE 1990 CLEAN AIR ACT AMENDMENTS ON DISTRIBUTIONS OF VISUAL IMPAIRMENT

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The Acid Rain Provisions (Title IV) of the 1990 Clean Air Act Amendments (1990 CAAA) focus on emission policies designed to reduce the amount of deposition of acidifying pollutants, particularly in the Northeast. The primary strategy is a significant reduction in SO_2 emissions, with lesser reductions scheduled for NO_x emissions. However, lessening of acid deposition is not the only important benefit of the emission control strategy. Decreasing SO_x and NO_x emissions will decrease atmospheric concentrations of sulfate and nitrate particles, which account for much of the visibility reduction associated with regional haze. Although one can get a qualitative sense of how visibility might improve by examining historical large-scale trends in regional emission totals and regional visibility (Trijonis *et al.*, 1990), quantification of the expected improvement requires model simulations. One must model the spatial and temporal patterns of emissions reductions; the relevant pollutant transport, transformation, and removal processes in the atmosphere; and the changes in visibility associated with the changes in particulate loading (Chestnut *et al.*, 1995). For this initial examination of the visibility improvement at Shenandoah National Park associated with the Phase I and Phase II SO_2 emission reductions, we have linked emission trend projections taken from ongoing analysis of the 1990 CAAA at Argonne National Laboratory, regional transport modeling with the Advanced Statistical Trajectory Regional Air Pollution (ASTRAP) model (Shannon, 1985), and visual impairment modeling with the Visibility Assessment Scoping Model (VASM) (Trexler and Laulainen, 1992; Trexler and Shannon, 1995).

1. EMISSIONS MODELING

It is convenient for input to the regional transport modeling to specify Phase I SO_2 emission reductions for individual coal-burning power plants and Phase II reductions aggregated at the state level. Because of the banking of emission allowances, early implementation of emission reductions due to fuel switching or scrubber construction, and normal plant life cycles, the Phase I reductions are spread over a number of years rather than being a single-step reduction in 1995, while Phase II reductions were always expected to cover a span of years. Our inventories of emission reductions at 5-yr intervals from 1995 through 2010 are summarized in Table I.

TABLE I: Emission reduction trends used in this study (kt SO_2 yr^{-1}).

Year	Phase I Sources	Phase II Sources	Total Reduction
1995	2500	0	2500
2000	4000	1050	5050
2005	4100	1100	5200
2010	4170	1260	5430

We plan to expand our treatment of emission trends as research continues. Among the expected near-term improvements in our studies are inclusion of spatially disaggregated NO_x emission trends, anticipated Canadian emission trends (of minor importance to visibility at Shenandoah but critical for the Adirondacks and New England), and trends in the minor U.S. sources not affected by Phase I and Phase II. As emission allowances continue to be traded, an inventory of the actual spatial shifts of emissions (or emission reductions) associated with trades may be developed; if so, we can examine the combined effect of such trades on visibility.

2. REGIONAL TRANSPORT MODELING

We have chosen to apply ASTRAP in this modeling study because it has given good results in its application to various regional air pollution problems over the last two decades and because it can use emission information as described in the emissions modeling to calculate concentrations at resolutions (seasonal and substate) commensurate with the needs of VASM. Briefly, ASTRAP is a highly parameterized, assessment-friendly, long-term, long-range Lagrangian model. Horizontal dispersion is calculated by fitting spatial statistics to ensembles of individual trajectories calculated for each of a grid of virtual sources covering the emission region of interest. Trajectory statistics are adjusted for wet removal parameterized as a function of precipitation occurrence and amount. Vertical dispersion is calculated in a one-dimensional numerical integration that accounts for effective emission height, mixing, dry deposition, loss to the free troposphere, and linearized one-way chemical transformations, all parameterized as a function of season and time of day, as well as location (east-west differences). The statistics from the calculations of vertical and horizontal dispersion are combined with gridded seasonal emission inventories in calculations of mean seasonal concentrations of sulfate and nitrate. No explicit assumption is made within the model as to the forms of sulfate and nitrate, although what the model carries as nitrate is assumed to be a combination of nitric acid and particulate nitrate. For this preliminary study we have assumed that sulfate is in the form of ammonium sulfate, although observations during 1977-1980 indicated that ammonium bisulfate was quite common at some eastern locations (Johnson *et al.*, 1981).

Because we are focusing on the visibility effects of the Phase I and Phase II emission reductions and for now are assuming that other emissions remain constant and because ASTRAP is a linear model, we exercise ASTRAP with the changes in those sources at 5-yr intervals during 1995-2010 and subtract the resulting sulfate levels from those calculated with the complete 1990 SO_x emission inventory for the United States, Canada, and northern Mexico to estimate future concentration levels. In all simulations, trajectories are calculated for 11 yr of meteorological data (1980-1990).

Future meteorological conditions are inherently uncertain, although much relevant information is contained in past observational data. For pollutant variability unrelated to emission changes, we define meteorological variability to be short-term (within-season) pollutant variations and climatological variability to be year-to-year changes in pollutant averages and distributions. By exercising ASTRAP with meteorological data for different years, climatological variability can be estimated; the VASM approach described below simulates the effect of meteorological variability by Monte Carlo methods.

3. VISUAL IMPAIRMENT MODELING

One must choose a particular metric for expressing visibility. Prevailing visibility, the parameter routinely reported in meteorological observations, is useful for analysis of past large-scale trends (Trijonis *et al.*, 1990), but it has the undesirable feature of being in part a function of the availability of visual targets at various ranges. The total extinction coefficient (b_{ext}), visual range (Vr), and deciview (dv) level are all suitably quantitative, and with appropriate assumptions one can convert among the units. We have chosen to present the results of our analysis in deciviews, rapidly gaining acceptance in the visibility research community as the favored metric for visual impairment (Pitchford and Malm, 1992). The deciview level is defined as

$$dv = 10 * \mathrm{Ln}(A/B),$$

where A represents the combined attenuation from scattering and absorption by particulate species, absorption by background NO_2, and natural Rayleigh scattering, and B represents the natural Rayleigh scattering. The dv scale is analogous to the approximately logarithmic response of human vision to light attenuation.

VASM is a Monte Carlo model specifically designed to address visibility issues in assessment studies. The multiple versions of VASM have somewhat different specific Monte Carlo algorithms, but all versions have the same general form. Species-specific light attenuation is calculated for six particulate species as a function of particle concentration and (for hygroscopic species) relative humidity (RH). The combined attenuation is then expressed in deciviews (dv), and seasonal distributions of dv are produced. The Monte Carlo variabilities in this version of VASM can be summarized as follows:

- Each particulate species (sulfate, nitrate, elemental carbon, organic carbon, fine dust, and coarse dust) has log normal seasonal distributions of daily average, here based on 1989-1992 observations. For assessment of future conditions, the sulfate concentration is scaled by the ratio of ASTRAP results for the emissions of the future year to ASTRAP results for 1990 emissions.

- The daily Monte Carlo variations of concentrations of the various particulate species are partly correlated, because all can be affected by common local meteorological factors such as variations in the depth of the mixed layer.

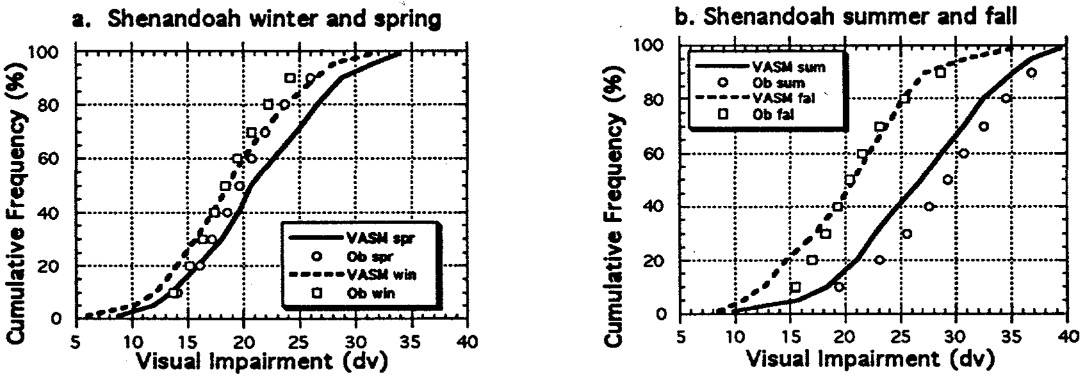
- The RH is given a Monte Carlo daily variation about the long-term seasonal means estimated from climatology; the seasonally typical diurnal cycle is imposed on the daily value to produce hourly varying RH.

- For simulations examining the effects of climatological variability, the seasonal means of each species are given normal variations about the corresponding long-term means, with a coefficient of variation of 0.10 as estimated for sulfate with ASTRAP.

An issue worthy of brief discussion is the determination of the appropriate time or period of the diurnal cycle most useful for simulations. We will compare our model simulations with transmissometer observations summarized by season. The observations were taken hourly throughout the diurnal cycle, although instrument malfunctions or related problems led to periods of missing data. The summaries are further reduced by elimination of observations affected by weather-related obstructions to visibility, such as fog or rain. On the other hand, it is logical to assume that in scenic areas visual impairment is much more important during daylight than at night. For simplicity in multiple Monte Carlo simulations and to speed execution of visual-impairment calculations (an important consideration when calculations are part of an on-line integrated assessment), it is most convenient to focus on a single time, such as noon. For these reasons we use slightly different but consistent versions of VASM here. In VASM the *dv* distribution for a single time of day will be more narrow than the *dv* distribution for the entire diurnal cycle, because a greater range of RH values will be simulated during the entire cycle than at a specific time of day.

For comparisons of VASM results with the transmissometer-derived cumulative frequencies of *dv*, we simulate seasonal hourly impairment distributions for the entire 24-h cycle. The transmissometer measurements cover portions of the period December 1988 through February 1993; the mean seasonal concentrations of particulate species as determined from 24-h filter packs taken twice weekly cover about the same period. Because both data sets, which are independently gathered, are incomplete, their summaries contain considerable uncertainty as to representativeness. Transmissometer data for spring 1989 were not used because inspection revealed unrealistic lack of variability. The seasonal comparisons show generally good agreement for all seasons (Figure 1).

We simulate visual impairment without direct consideration of concurrent meteorological factors other than RH, while statistical summaries of transmissometer data eliminate observations that include meteorological factors such as fog or precipitation. Elimination of fog cases probably biased transmissometer statistics toward better visual range, because of the RH effect on particle size and scattering. The bias resulting from elimination of precipitation cases is difficult to evaluate qualitatively, because precipitation is also associated with elevated RH, but raindrops and snowflakes are also very effective in removing particles by washout.


a. Shenandoah winter and spring

b. Shenandoah summer and fall

Figure 1: Comparison of VASM *dv* distributions at Shenandoah National Park for 1989-1992 with those observed by transmissometer for (a) winter and spring and (b) summer and fall.

4. RESULTS

We estimated the improvement in visual impairment at Shenandoah by comparing VASM simulation results for 1990 conditions with results expected for 2010 conditions, after completion of both Phase I and Phase II SO_2 emission reductions (Figure 2). ASTRAP simulations indicate that sulfate concentrations will be reduced about 40%. The sequences of Monte Carlo variations are constrained to be identical in the two cases to isolate the effect of the SO_2 emission reductions. The *dv* distributions exhibit a shift to lower visual impairment, ranging from about 1*dv* in winter to more than 2 *dv* in summer. Although this improvement may seem small in absolute numbers, the *dv* scale is logarithmic, and some observers have detected a difference of 1 *dv* in in slide tests using a scenic view with strong contrasts. It should be noted that the improvement that can be obtained solely by SO_2 controls is limited, because sulfate causes only about 40-50% of the visual impairment in the nonurban East. The remainder is due to other particulate species, NO_2 gas, and natural Raleigh scattering (Trijonis *et al.*, 1990).

Sometimes researchers have a particular interest in the change in the frequency of relatively dirty or relatively clean days; by selecting a critical deciview value, one can easily estimate such changes from the expected distributions. For 1990 emission levels, our simulations indicate that 24% of the time midday summer visual impairment at Shenandoah is worse than 30 *dv* . That level of visual impairment is expected to be exceeded only 11% of the time after Phase II SO_2 emission controls are fully implemented. Specification of extinction values for RH above 90% is a contentious matter, and thus modeling uncertainty is higher for the polluted tail of the *dv* distribution. In addition, analysis of observations for such periods is difficult because of the frequent occurrence of meteorological phenomena, primarily fog.

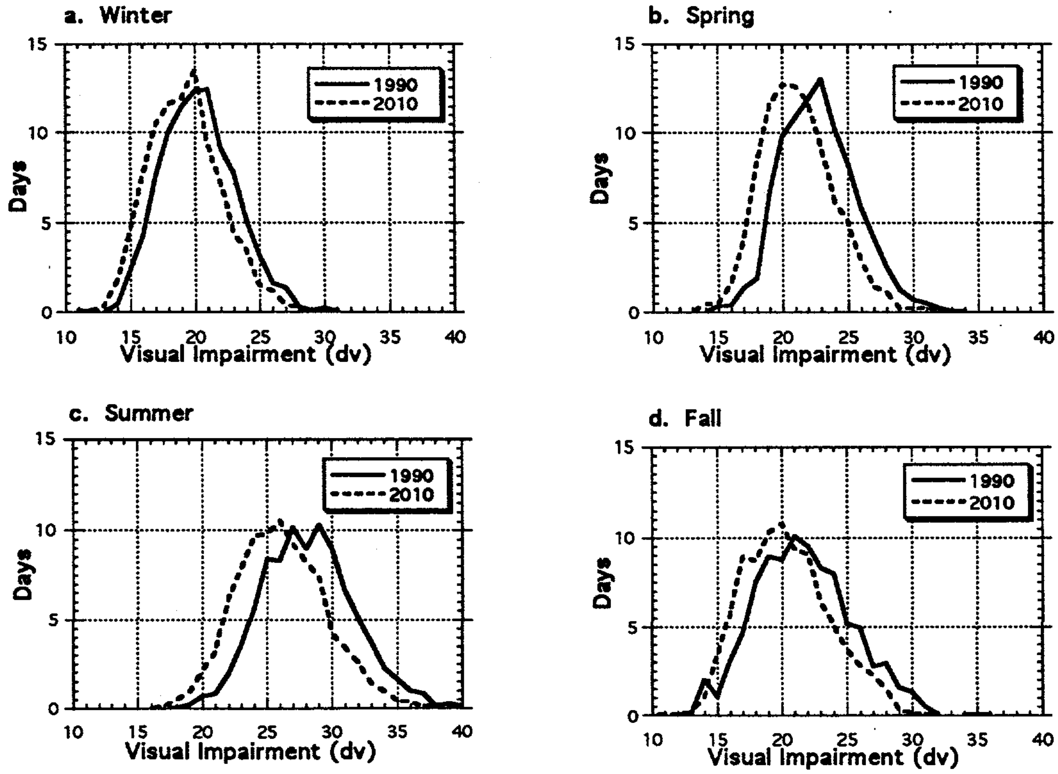


Figure 2: VASM calculations of the midday visual impairment distribution at Shenandoah National Park for 1990 emission conditions and that expected after implementation of Phase I and Phase II SO_2 emission reductions for (a) winter, (b) spring, (c) summer, and (d) fall.

Our calculations in Figure 2 correspond to a multiyear average. For clarity in assessment and policy analysis, expected mean distributions are the most useful modeling output because changes expected after a sufficiently long period of averaging can be depicted clearly. Visual impairment distributions for a single season, on the other hand, can be expected to exhibit marked irregularities (Shannon and Trexler, 1995). Figure 3 compares two Monte Carlo realizations of single-summer simulations (with inclusion of a 10% coefficient of variation of seasonal averages for each particulate species, a value consistent with ASTRAP simulations for sulfate), to illustrate typical year-to-year variability unrelated to emission changes. Both forms of presentation are useful in demonstrating expected outcomes and potential variations about those outcomes.

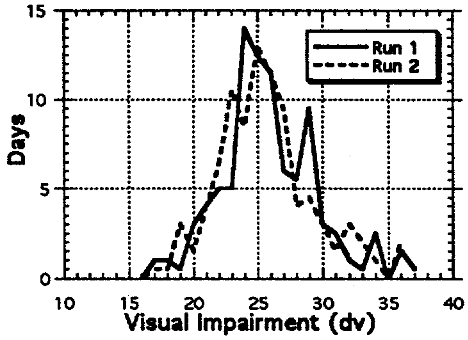


Figure 3: Typical climatological variation of summer distribution of midday visual impairment at Shenandoah, as illustrated by two VASM model runs with different random variations.

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