ANL/ER/CP--90106

CONF-9606207--1

MODELING VISIBILITY FOR EMISSIONS POLICY ASSESSMENT

by

J. D. Shannon

Environmental Research Divison
Argonne National Laboratory
Argonne, IL 60439

MODELING VISIBILITY FOR EMISSIONS POLICY ASSESSMENT

Jack D. Shannon
Environmental Research Division
Argonne National Laboratory
Argonne, IL 60439
USA

ABSTRACT: An efficient method for simulating and assessing regional-scale visual impairment is described. The method applies Monte Carlo methods to generate realistic within-season distributions of visual impairment and requires input only of distributional statistics from particle monitoring data, relative humidity climatology, and seasonal mean concentrations predicted with a regional transport model for the various emission scenarios examined. Simulated distributions of visual impairment for a representative rural site in the eastern United States are demonstrated to compare favorably with observations.

1. Introduction

An atmospheric environmental problem common to many regions, particularly large urban areas, is reduction of visibility. Although it is not a direct health risk (save perhaps in impacts on transportation safety in extreme cases), elevated concentrations of some of the pollutant species impairing visibility, such as particulate sulfate, are associated with adverse health effects; and reduced visibility may significantly impact the "quality of life." As industrialization and urbanization increase, further visual impairment can be anticipated unless appropriate emission control measures are taken; however, significant emission reductions are not, as a rule, cost-free. Thus, it becomes important to examine the effectiveness of various control options. Although in some localized cases, visual impairment may be predominantly caused by a single pollutant, more commonly such impairment results from a mix of pollutants that are associated with different emission sectors, for which the role of controllable anthropogenic sources may be dominant, significant, or minor. The visibility assessment process described here will focus on a single pollutant; however, the approach is designed to evaluate more complex control strategies.

This paper describes an approach quantifying in physical terms one of the benefits (improved visibility) of emission control strategies. We do not attempt in this paper to quantify visibility benefits in economic terms for ultimate comparison with costs. In a complete assessment, such efforts would logically be linked with cost models for the various emission control options, and, where appropriate, with assessment of other benefits, such as reductions in acid rain. In an ongoing assessment of acid rain legislation by a team of researchers in which we are applying the techniques described here, quantification of the economic benefits of calculated improvements in visibility is included, along with control cost estimates and assessment of benefits in other areas, such as reduced lake acidification (TAF, 1995).

The most focused visibility research program currently active in the United States is that of the Grand Canyon Visibility Transport Commission (Mathai, 1996), which is examining source-receptor relationships and the costs and benefits of various control strategies to maintain or improve visibility at the Grand Canyon National Park and other scenic areas of the Colorado Plateau of the interior of the American West. On the plateau, visual impairment (which is much less than that typically encountered in large urban areas but at times is significant for viewing distant scenic vistas) results from a wide mix of pollutants and is regional in scale, and natural sources are significant for most of these species.

We have chosen to illustrate our visibility assessment approach with examples from an assessment of acid rain legislation in the United States. The Acid Rain Provisions in Title IV of the 1990 Clean Air Act Amendments (1990 CAAA) enacted by the U.S. Congress are designed to reduce the amount of deposition of acidifying pollutants, particularly in the northeastern United States. The primary strategy is a significant reduction in sulfur dioxide emissions in the eastern United States, with lesser reductions scheduled for emissions of nitrogen oxides (NOx); independently, SO_2 emissions in Canada will also be reduced. However, lessening of acid deposition is not the only important benefit of the emission control strategies. Decreasing emissions of sulfur oxides (SO_x) and NO_x will decrease atmospheric concentrations of sulfate and nitrate particles, which account for much of the visual impairment associated with regional haze in eastern North America. Although one can get a qualitative sense of how visibility might improve by examining concurrent historical large-scale trends in regional emission totals and regional visibility (Trijonis *et al.*, 1990), quantification of the expected improvement requires integrated 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). In this example, we have linked SO_2 emission trend projections from ongoing analysis of the 1990 CAAA at Argonne National Laboratory, SO_2 emission trend projections for Canada produced by Environment Canada, regional atmospheric source-receptor modeling for sulfate 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). We apply our visibility assessment method for a scenic rural site (Shenandoah National Park, about 125 km southwest of Washington, D.C.) to examine the expected visibility improvement associated with the Phase I (to be implemented by 1995) and Phase II (to be implemented by 2010) SO_2 emission reductions. Although NO_x emission reductions are also mandated by the legislation, we are limiting our example to the effects of the SO_x emission reductions on visibility.

2. Emissions modeling

Because the Phase I SO_2 emission reductions effectively were specified for individual major power plants, we can resolve the Phase I emission reduction field in great detail. In contrast (and in a much more typical assessment application), the spatial details of Phase II reductions are highly uncertain at this time and cannot be meaningfully resolved more finely than statewide aggregation. The Canadian emissions projections are aggregated provincial totals. For our presentation here, we will illustrate modeled visual impairment for 1990 emissions and for 2010 emission projections (*i.e.*, prior to enaction of the 1990 CAAA and after full implementation of the SO_x portion of its Acid Rain Provisions, as summarized in Table I). We use sulfur rather than SO_2 in the table because typically 1-2% of SO_x emissions consist of primary sulfate particles rather than SO_2 gas. The Mexican emissions inventory is limited to northern Mexico and is taken from an inventory developed by the Grand Canyon Visibility Transport Commission (GCVTC), with some modifications recommended by various technical committees of the GCVTC. We do not attempt to project Mexican emissions trends because current estimates of such emissions are much more uncertain than for U.S. and Canadian emissions and because the effect of Mexican emissions on visual impairment in the eastern United States is quite minor, largely because of distance. Mexican emissions are of considerably more importance when visibility in the western United States is examined.

The SO_x emissions inventory for 1990 is spatially detailed in a three-dimensional grid for each state or province (northern Mexico is treated as a single "province"), with horizontal spacing of about 120 km and six layers to 800 m in the vertical. Expected emissions changes over the two decades are a combination of the Phase I reductions, detailed to individual major sources, and aggregated state or provincial Phase II and Canadian reductions, which are assumed to have the same relative distribution within a state or province as the 1990 emissions. The seasonal emissions pattern for 2010 is assumed to be that of 1990 (*i.e.*, generally greatest in summer and least in spring and fall).

Table I: Anthropogenic S annual emissions (ktonnes S/yr).

	United States	Canada	Northern Mexico	Total
1990	10,500	3,200	320	14,000
2010	7,800	2,800	320	10,900

3. Regional transport modeling

We choose to apply ASTRAP to calculate regional source-receptor relationships for our visibility modeling studies because the periodically upgraded model has given good results in its application to various regional air pollution problems over almost two decades (*e.g.*, Shannon, 1981; Shannon and Streets, 1987; Shannon and Lesht, 1988; Shannon and Sisterson, 1992; and Shannon and Voldner, 1995) and because emissions information as commonly resolved in most inventories (seasonal and annual totals with spatial resolution of 100-300 km) is suitable input to ASTRAP for calculating average particle concentrations at the seasonal resolution commensurate with the input needs of VASM. Briefly, ASTRAP is a highly parameterized, assessment-friendly, long-term, long-range Lagrangian model (Shannon, 1985). Horizontal dispersion is calculated by fitting seasonal mean plumes to ensembles of individual trajectories calculated for each of a grid of virtual sources covering the emission region of interest (here the contiguous United States, Canada, and northern Mexico). 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, convective loss to the free troposphere, and linearized one-way chemical transformations, with vertical profiles of eddy diffusivity, deposition velocities, and transformation rates all parameterized as functions of season, time of day, and location (different rates for relatively polluted and moist eastern North America and relatively clean and dry western North America). The parameterization rates are based on field studies, mass budget analysis, and climatology. The vertical and horizontal dispersion statistics are combined with seasonal emissions inventories in calculations of mean seasonal atmospheric concentrations of emitted pollutants and their transformation products and cumulative wet and dry deposition, with the species of interest here being atmospheric sulfate. The ASTRAP simulations of annual sulfate concentrations over regional scales compare quite favorably in Figure 1 with monitoring data and with the results of a much more detailed Eulerian model, the Regional Acid Deposition Model (Dennis, R., 1996, *personal communication*). Because ASTRAP is a linear model, we can exercise ASTRAP with emissions decreases (relative to 1990 emissions) during 1990-2010 and subtract the resulting calculated sulfate levels from those calculated with the complete 1990 SO_X emissions inventory for the United States, Canada, and northern Mexico to estimate concentration levels for 1990-2010.

Future meteorological conditions are inherently uncertain, but the stochastic behavior of meteorological conditions should reflect the statistics of past behavior, or climatology. If we can eliminate or adjust for changes in pollutant behavior associated with emissions changes, then short-term (within-season) pollutant variations can be considered meteorological, and year-to-year changes in pollutant seasonal and annual averages and distributions can be considered climatological. By exercising ASTRAP with meteorological data for different years, climatological variability of air pollution can be estimated. We calculate climatological coefficients of variation (standard deviation/mean) of seasonal average sulfate concentrations of typically 0.08-0.18 in the eastern United States, with the higher relative variabilities occurring in more remote areas and in the transition seasons, spring and autumn. In this ASTRAP application, trajectories are calculated for 11 years or 44 seasons of meteorological data (1980-1990). Our calculations represent the climatologically expected concentration patterns corresponding to the emission fields; the actual concentration patterns during individual seasons would differ because of the departure of the wind and precipitation patterns of individual seasons for those years from long-term climatology. (There would be differences because of modeling shortcomings as well, of course.) When appropriate meteorological, emission, and monitoring data exist, one would probably choose to exercise the transport model with the actual sequences of meteorological fields for each season, rather than long-term climatology, to eliminate climatological uncertainty from that portion of the analysis. However, simulations for the future cannot avoid climatological uncertainty, and thus it should be considered in determining overall assessment uncertainty. Meteorological (within-season) variability is not simulated by ASTRAP, which calculates seasonal averages directly; instead the VASM approach described in the section to follow simulates meteorological variability by Monte Carlo methods.

No explicit specification is made within ASTRAP as to the form of sulfate; rather, concentrations of the combined sulfate ion portion of all atmospheric sulfate, whether ammonium sulfate, ammonium bisulfate, or sulfuric acid, are calculated. All of the sulfate species are of a typical size range that is effective in attenuating light, but the particle masses associated with their concentrations, required for visual impairment formulations, differ somewhat. A complete neutralization of sulfate to ammonium sulfate would imply a value of approximately 1.38 for the ratio of ammonium sulfate mass to sulfate mass, partial acidification to ammonium bisulfate would imply a corresponding ratio of 1.20, while sulfuric acid droplets would imply a ratio of 1.02. Measurements of sulfate particle speciation during the period of 1977-1980 indicated that acidic sulfate was quite common at many locations in the eastern United States, particularly during the warm months (Johnson *et al.*, 1981). A recent study found neutralization of sulfate to be greater in a large urban area than in two semi-rural areas, presumably because of the greater availability of ammonia in the urban area (Liu *et al.*, 1996). When ASTRAP results are applied in VASM for eastern U.S. sites, we assume seasonal factors of (1.35, 1.25, 1.20, 1.25) to convert modeled sulfate ion concentration to equivalent sulfate particle mass for winter through autumn, respectively, which is equivalent to assumptions of almost total neutralization to ammonium sulfate during winter, acidification to ammonium bisulfate during summer, and intermediate values during the transition seasons. When modeled in ASTRAP, nitrate represents a bulk combination of nitric acid and particulate nitrate. Although sulfuric acid droplets can be found in the atmosphere, atmospheric nitric acid is a gas and does not impair visibility. When ASTRAP simulations of bulk nitrate are used in VASM, we first assume that the fraction of the modeled bulk nitrate that is particulate nitrate is (0.4, 0.2, 0.1, 0.2) for winter through autumn, respectively, on the basis of empirical comparisons of modeled bulk nitrate with observations of particulate nitrate, and then assume complete neutralization of particulate nitrate to ammonium nitrate during all seasons, which implies a mass ratio of nitrate particles to the nitrate portion of the particles of 1.29.

4. Visual impairment modeling

One must choose a particular metric for expressing visibility. Prevailing visibility, routinely reported in meteorological observations, is useful for analysis of past large-scale trends (Trijonis *et al.*, 1990) but has the undesirable feature of being in part a function of the availability of visual targets at various distances. 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 (*dv*), rapidly gaining acceptance in the visibility research community as the favored metric (Pitchford and Malm, 1992). The *dv* scale is analogous to the approximately logarithmic response of human vision to light attenuation:

$$dv = 10 \cdot \mathrm{Ln}\,(A\ /\ B)\ , \qquad (1)$$

where A represents the combined optical extinction or attenuation from scattering and absorption by particulate species, absorption by background NO_2, and Rayleigh scattering (the natural scattering of light by air molecules, also called blue-sky scatter); and B represents Rayleigh scattering. For suitable assumptions about the radiative characteristics of a target and the background (Trijonis *et al.*, 1990), equivalent expressions of *dv* are

$$dv = 10 \cdot \mathrm{Ln}\,(391\ \mathrm{km}\ /\ Vr)\quad \text{or} \qquad (2)$$

$$dv = 10 \cdot \mathrm{Ln}\,(b_{ext}\ /\ 0.01\ \mathrm{km}^{-1}), \qquad (3)$$

For western sites on the Colorado Plateau, the appropriate Rayleigh value is usually taken as 10 $(\mathrm{Mm})^{-1}$. One could assume the same value elsewhere; however, most of the eastern United States is considerably lower in elevation than the Colorado Plateau and thus has a thicker atmosphere above. We have chosen to use a Rayleigh value for eastern locations of 12 $(\mathrm{Mm})^{-1}$. The effects of assuming a larger Rayleigh value, all slight, are to increase b_{ext}, decrease *Vr*, and decrease *dv* (because a constant is being added to both numerator and denominator in the *dv* definition).

The VASM model is a Monte Carlo model specifically designed to simulate visual impairment for assessment studies (Trexler and Laulainen, 1992; Shannon and Trexler, 1995; Shannon *et al.*, 1996). Several researchers are applying VASM for various applications in differing hardware/software combinations, and thus multiple versions of VASM with somewhat different specific Monte Carlo algorithms exist, but all versions have the same form:

(1) Monte Carlo techniques are used to generate multiple realizations of short-term concentrations of six particle species (sulfate, nitrate, elemental carbon, organic carbon, fine dust, and coarse dust) and relative humidity (RH),

(2) Species-specific light attenuation is calculated as a function of particle concentration and (for hygroscopic species) RH, and

(3) The combined attenuation from all species is converted to deciviews (*dv*), and seasonal distributions of *dv* are produced.

In this VASM version the daily concentrations of each particle species for each season at the receptor sites of interest are assumed to be lognormally distributed, with the distribution parameters developed from twice-weekly 24-hour concentrations from the Interagency Monitoring of PROtected Visual Environments (IMPROVE) network (Eldred *et al.*, 1994) for 1989-1994. The dust concentrations are calculated as residuals rather than directly measured. Fine dust is that portion of mass concentrations of particulate matter less than 2.5 μm in diameter ($PM_{2.5}$) not attributed to sulfate, nitrate, elemental carbon, and organic carbon. In adjusting for the mass contributions from those species, the sulfate and nitrate concentrations are multiplied by the speciation factors described in the preceding section; and organic carbon is multiplied by 1.4, as recommended by the GCVTC Technical Committee. Coarse dust is defined as the concentration of particulate latter less than 10 μm in diameter (PM_{10}) minus $PM_{2.5}$ concentration.

For assessment of future conditions, concentrations of modeled particle species (here only sulfate) are scaled by the seasonal ratios of ASTRAP mean concentrations calculated for the emissions of the future year divided by the corresponding ASTRAP results for 1990 emissions (appropriate for the period of monitoring data). In this way, we rely on relative rather than absolute model output; atmospheric transport model results are generally more credible for relative values than for absolute values. Because our emissions scenarios do not change the emissions of other species, the future concentration distributions of the other five particle species are ensembles of realizations developed with statistical parameters describing their current distributions.

The Monte Carlo techniques allow daily concentrations of the various particulate species to be partly correlated within seasons because concentrations of all species can be affected by common local meteorological factors such as variations in the depth of the mixed layer. At remote coastal locations for which anthropogenic or terrestrial emission regions lie in only some upwind sectors, wind direction may also force significant correlations among species. Other factors may result in anticorrelations, however. For instance, in warm humid conditions favorable for SO_2 oxidation and thus higher sulfate concentrations, Henry's law considerations lead one to expect a greater than normal fraction of total nitrate to be gaseous nitric acid, and thus daily sulfate and particulate nitrate concentrations might be negatively correlated. Strong winds increase ventilation and thus tend to reduce most concentrations, but such winds increase resuspension of coarse dust particles and subsequent atmospheric concentrations of coarse dust. In monitoring data at Shenandoah, daily concentrations of elemental carbon, organic carbon, and fine dust exhibit seasonal correlations with daily sulfate concentrations of about 0.5 to 0.6, while fine-particle nitrate and coarse dust show almost no correlation with sulfate.

Relative humidity is given a Monte Carlo daily variation about long-term seasonal means taken 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 the coefficients of variation estimated for sulfate and nitrate from ASTRAP simulations for each individual meteorological year of the period 1980-1990, and taken from measurements for the other species with the assumption of no significant emissions changes (*i.e.*, the observed year-to-year variations are attributed to climatological variability).

The proper forms of the functions relating extinction to relative humidity for the hygroscopic species are somewhat contentious. A simple exponential form has been recommended by Malm *et al.* (1994):

$$b_{ext} = 3 \cdot fn \cdot SO_4^{2-} + 3 \cdot fn \cdot NO_3^- + (2 + fn/2) \cdot OC + 10 \cdot EC + 2 \cdot FD + 0.6 \cdot CD \qquad (4)$$

and

$$fn = \max\{1, 0.7/(1 - 0.01 \cdot RH)\} \text{ for } RH \leq 90,$$

where extinction (b_{ext}) is expressed in $(Mm)^{-1}$, where SO_4^{2-}, NO_3^-, OC, EC, FD, and CD represent concentrations (in $\mu g\ m^{-3}$) of sulfate, nitrate, organic carbon, elemental carbon, fine-particle ($PM_{2.5}$) dust, and coarse-particle (PM_{10} - $PM_{2.5}$) dust, respectively; and where SO_4^{2-}, NO_3^-, and OC have been converted to equivalent particle mass as described elsewhere. Malm *et al.* (1994) recommend that the extinction function not be applied for RH higher than 90% (*fn* would be undefined at RH = 100%), under the assumption that weather-related obstructions to visibility would be occurring for RH above 90%. Note that the *fn* function is constant for RH < 30%. Because a visibility assessment ultimately compares visibility distributions associated with two or more emission scenarios, what is assumed about such matters as adjustments for weather-related visual impairment is much less important than ensuring that the same assumption is made for both scenarios.

Laboratory data of McMurray and Lohenthal (1995) also indicate an exponential RH extinction function for SO_4^{2-}, NO_3^-, and OC, although not as steep as in the fomulation by Malm *et al.* (1994). We have chosen to fit polynomial functions to the laboratory data to apply in this version of VASM. The functions are compared in Figures 2a and 2b; note that the assumptions for elemental carbon, fine-particle dust, and coarse-particle dust are identical in the two approaches. The functions are made constant for RH < 20%. The data of McMurray and Lohenthal (1995) indicated a very slight exponential form for fine dust, but we have chosen to use the constant value recommended by Malm *et al* (1994). The McMurray-Lohenthal functions are plotted for RH values up to 98% and thus ultimately reach slightly greater values than the Malm *et al.* (1994) function maxima at 90% RH.

An issue worthy of discussion is the determination of the appropriate time or period of the diurnal cycle most useful for simulations. Transmissometer observations of visual impairment, with which our simulations can be compared, are taken hourly throughout the diurnal cycle; however, in scenic remote areas visual impairment is much more important during daylight than at night. 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. The VASM model is currently being applied in such an integrated assessment, the Tracking and Analysis Framework (TAF, 1995). In VASM, the seasonal *dv* distribution for a single time of day will be somewhat more narrow than the seasonal *dv* distribution for the entire diurnal cycle because a greater range of RH values will be simulated during the diurnal cycle than at a specific time of day.

How well do the Monte Carlo techniques in VASM reproduce observed within-season distributions of visual impairment? We can evaluate VASM with *dv* cumulative distributions from transmissometer measurements at Shenandoah. Because the transmissometer readings are taken hourly both day and night, we simulate seasonal hourly visual impairment distributions for the entire 24-hour cycle with VASM. The transmissometer measurements for Shenandoah National Park cover portions of the period of December 1987 through May 1993; the seasonal particle distributional parameters input to VASM are determined from analysis of 24-hour filter packs taken twice weekly over about the same period.

Both data sets, which are independently gathered, are incomplete. In addition, VASM simulates visual impairment without direct consideration of concurrent meteorological factors other than RH, while the statistical summaries of IMPROVE transmissometer data treat observations with RH > 90% as weather-impaired and eliminate such observations, along with other observations in which extinction appears to be too high, too low or to change too rapidly, in observation summaries. The IMPROVE RH criterion is necessarily arbitrary, because RH measurements at a single point must be used to characterize a linear path over which RH would not be expected to be constant. Visual impairment by weather would involve mainly fog and precipitation. Fog might not exist even when station RH > 90%, while precipitation might be falling through the transmissometer path even when station surface RH < 90%, but overall the criterion is probably conservative (*i.e.*, it would be expected to eliminate more cases than are actually affected by fog or precipitation). Inclusion of high RH cases in VASM probably shifts our results (relative to "non weather-impaired transmissometer summaries") toward a greater frequency of high *dv* values because of the RH effect on particle size and scattering. Any VASM biases resulting from nonexclusion of precipitation cases is difficult to evaluate qualitatively because precipitation is associated with elevated RH but low particle concentrations because raindrops and snowflakes are very effective in removing particles by washout. Overall, one might expect that VASM simulations would exhibit a distribution somewhat broader than that of non weather-impaired transmissometer summaries but narrower than transmissometer summaries for all cases. While it is important to recognize such characteristics in model evaluation, application of VASM for scenario comparisons focuses on relative distributions of visual impairment, rather than absolute distributions, and thus the specific treatment of high RH becomes less critical.

Notwithstanding the above caveats, the seasonal comparisons show generally good agreement (Figures 3a-3d). The multiple transmissometer distributions also support our ASTRAP modeling analyses that indicate that climatological variability of visual impairment distributions (*i.e.*, year-to-year differences) can be large. This must be kept in mind when evaluating the expected detectability of visual impairment resulting from emissions reductions.

5. Results

We estimate the anticipated improvement in visual impairment at Shenandoah by comparing VASM simulation results for 1990 emissions with results expected in 2010 after completion of both Phase I and Phase II SO_2 emissions reductions. The ASTRAP simulations indicate that sulfate concentrations at Shenandoah will be reduced about 35% by 2010, about the same as the emissions reductions in eastern North America. The sequences of Monte Carlo variations within seasons are constrained to be identical in the two cases to isolate the effect of the SO_2 emissions reductions, and the results of VASM have been smoothed for clarity in presentation. The seasonal *dv* distributions (Figures 4a-4d) exhibit a shift to lower visual impairment of about 2 *dv*, somewhat more in summer and a bit less in the other seasons. Although this improvement as depicted graphically may seem small, one should remember that the *dv* scale is logarithmic. Note also 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), none of which is changed in this evaluation. The expected *dv* distributions for the interim years would lie between the results for 1990 and 2010. Actual realizations of annual distributions would include the effects of climatological variability and would not be expected to vary so smoothly.

Sometimes researchers have a particular interest in the change in the frequency of relatively dirty or relatively clean days; by selecting a critical *dv* value, one can easily estimate such changes from the expected distributions. For 1990 emissions levels, our simulations indicate that midday summer visual impairment at Shenandoah is worse than 30 *dv* 19% of the time. That level of visual impairment is expected to be exceeded only 13% of the time after Phase II SO_2 emissions controls are fully implemented. Specification of extinction values for RH above 90% is a contentious matter, however, 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 reducing visibility, particularly fog. If we arbitrarily define clean summer days at Shenandoah as days with midday visual impairment less than 15 *dv*, their expected frequency would improve from 10% in 1990 to 15% after full implementation of the SO_x emissions reductions mandated by the 1990 CAAA. In general, the relative changes in frequencies of the extremes of VASM-generated distributions for alternate emissions scenarios are larger than changes in central statistics such as means or medians.

Our results in Figure 4 correspond to a multiyear average. For 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, exhibit marked irregularities (Shannon and Trexler, 1995) in both observations and simulations. Both forms of output are useful in demonstrating expected outcomes and potential variations about those outcomes.

6. Extension of the ASTRAP/VASM approach to other locations

How would one apply this integrated modeling approach for a different area, specifically the Pacific Rim of Asia, and at receptor locations for which some desired air quality statistics might not be available? For meaningful assessment results, the emissions inventory for the pollutants whose concentration averages are modeled should have a spatial resolution of 100-300 km if possible; appropriately resolved fields are generally available for SO_2 and NO_x (Kato and Akimoto, 1992; Bhatti *et al.*, 1992). In the absence of additional information, one then could assume that the spatially disaggregated emission field would scale up or down in the future according to projected national totals; if available, a regionally differentiated emissions policy could be easily treated and would reduce assessment uncertainty.

The ASTRAP model of atmospheric pollutant transport could be exercised for locations in east Asia to calculate seasonal concentrations of sulfate and nitrate and perhaps elemental carbon (inventory availability permitting) with meteorological data sets (wind and precipitation) for temporal and spatial resolutions different than those described above, provided that the fields were updated at least daily and preferably more often. Some of the parameterizations and parameterization rates might need to be adjusted because such parameterizations are implicit functions of the data resolution. Calculation of regional source-receptor relationships for organic carbon particles is more problematic, both because suitable inventories of precursor gases may not be available and because the portion of the observed concentrations due to natural emissions is thought to be significant but is difficult to quantify, and thus regional modeling uncertainty is quite high. We would expect that dust from the Gobi Desert would be a much more important factor in visual impairment than is dust in the eastern United States. We would probably choose not to model the seasonal concentrations of either fine or coarse dust but rather to assume that their statistical behavior in the future would be similar to their behavior in the past. Alternately, a different transport model could be used for any or all of the pollutants impairing visibility, provided that it could be exercised with the emission projections as finally resolved and could produce seasonal mean concentrations of modeled pollutants for input to VASM. It is likely, for example, that RAINS-ASIA, the Regional Air Pollution INformation and Simulation Model adapted for Asia (Foell *et al.*, 1996) could satisfy the needs for atmospheric transport modeling in our visibility assessment approach.

The VASM structure itself could probably be used without major change, but all of the statistical parameters used to create the within-season distributions of the visibility-impairing species should be specific to the locations of interest. If some of the pollutant monitoring data from which such statistics are developed are not available for a particular location, then reasonable estimates could probably be made from observations elsewhere, although at a cost of increased uncertainty in the assessment. Parameterizations of the correlations of short-term concentrations among species would also be more uncertain if appropriate local monitoring data were not available; however, there would appear to be no theoretical obstacles to application of this visibility assessment approach for selected locations on the Pacific Rim of Asia or elsewhere.

ACKNOWLEDGMENTS: This work was supported by the Office of Planning and Environment, Office of Fossil Energy, U.S. Department of Energy, under contract W-31-109-Eng-38. The VASM concept on which this approach is based was developed by Ed Trexler of that office. Data were provided by John Molenar of Air Resources Specialists, Inc., Jim Sisler of the U.S. National Park Service, Libby Greenwood of Environment Canada, and Larry Montgomery of the U.S. Environmental Protection Agency.

REFERENCES:

Bhatti, N., Streets, D.G., and Foell, W.K., 1992: Acid Rain in Asia. *Environ. Management,* **16**, 541-562.

Chestnut, L.G., Dennis, R.L., and Latimer, D.A., 1995: Economic benefits of improvements in visibility: Acid Rain Provisions of the 1990 Clean Air Act Amendments. In: *Proceedings of the International Specialty Conference on Aerosols and Atmospheric Optics: Radiative Balance and Visual Air Quality*, Snowbird, Utah, Sept. 26-30, 1994, Air and Waste Management Association, Pittsburgh, 791-802.

Eldred, R.A., Cahill, R.A., Feeney, P.J., and Flocchini, R.G., 1994: Comparison between PM10 and PM2.5 Aerosols in the IMPROVE Network. In: *Proceedings,* *International Specialty Conference on Aerosols and Atmospheric Optics: Radiative Balance and Visual Air Quality*, Snowbird, Utah, Sept. 26-30, 1994, Air and Waste Management Association, Pittsburgh, 878-889.

Foell, W., Green, C., Amann, M., Bhattacharya, S., Carmichael, G., Chadwick, M., Cinderby, S., Haugland, T., Hettelingh, J.-P., Hordijk, L., Kuylenstierna, J., Shah, J., Shrestha, R., Streets, D., and Zhao, D., 1996: Energy use, emissions, and air pollution reduction strategies in Asia. *Water Air Soil P.ollut*, **85**, 2277-2282.

Johnson, S.A., Kumar, R., Cunningham, P.T., and Lang, T.A., 1981: *The MAP3S Aerosol Sulfate Acidity Network: A Progress Report and Data Summary*. Argonne National Laboratory Report ANL-81-63, Argonne National Laboratory, Argonne, Il., 140 pp.

Kato, N., and Akimoto, H., 1992: Anthropogenic emissions of SO_X and NO_X in Asia: emission inventories. *Atmos. Environ.*, **26A**, 2997-3017.

Liu, L.-J., Burton, R., Wilson, W.E., and Koutrakis, P., 1996: Comparison of aerosol acidity in urban and semi-rural sites. *Atmos. Environ.*, **30**, 1237-1245.

Malm, W.C., Sisler, J.F., Huffman, D., Eldred, R.A., and Cahill, T.A., 1994: Spatial and seasonal trends in particle concentration and optical extinction in the United States. *J. of Geophys.Res.*, **99(D1)**, 1347-1370.

Mathai, C.V., 1996: The Grand Canyon Visibility Transport Commission and visibility protection in Class I areas. *Environ.Manager*, **1**, 20-31.

McMurray, P. and Lohenthal, D., 1995: Results presented in *Aerosol Extinction Efficiency Workshop, DOE, February 8-9, 1995, Notes*. Packfic Northwest Laboratory, Richland, Wash.

Pitchford, M., and Malm, W., 1992: *Development and Application of a Standard Visual Index*, Conference on Visibility and Fine Particles, Vienna, Austria.

Shannon, J.D., 1981: A model of regional long-term average sulfur atmospheric pollution, removal, and net horizontal flux. *J. Atmos. Environ.* **15**, 689-701.

Shannon, J.D., 1985: *User's Guide for the Advanced Statistical Trajectory Regional Air Pollution (ASTRAP) Model.* U. S. Environmental Protection Agency Report EPA/600/8-85/016 (NTIS PB85-236784/XAB).

Shannon, J.D., and Streets, D.G., 1987: Climatological variability in the evaluation of cost effectiveness of emission control strategies to reduce acid deposition. In: *Air Pollution Modeling and Its Applications V* (C. De Wispelaere, F.A. Schiermeier, and N.V. Gillani, eds.), Plenum Press, New York, 33-44.

Shannon, J. D., and Lesht, B.M., 1988: Modeling the relationship between sources and receptors of wet deposition of S and NOx-N in the intermountain west of the United States. In: *Air Pollution Modeling and Its Applications VI* (C. De Wispelaere, ed.), Plenum Press, New York, 333-343.

Shannon, J. D. and Sisterson, D.L., 1992: Estimation of S and NOx-N deposition budgets for the United States and Canada. *Water Air Soil Pollut.*, **63**, 211-235.

Shannon, J.D., and Trexler, E.C., Jr., 1995: Climatological variability in regional air pollution. In: *Proceedings of the 6th International Meeting on Statistical Climatology,* Galway, Ireland, June 19-23, 1995, World Meteorological Organization, Geneva, 511-514.

Shannon, J.D., and Voldner, E.C., 1995: Modeling atmospheric concentrations of mercury and deposition to the Great Lakes. *Atmos. Environ.*, **29,** 1649-1661.

Shannon, J.D., Camp, J., and Trexler, E.C. Jr., 1996: Effects of the 1990 Clean Air Act Amendments on distributions of visual impairment. In: *Proceedings of the 9th Joint Conference on Applications of Air Pollution Meteorology with A&WMA*, Atlanta, GA, Jan. 28 - Feb. 2, 1996, American Meteorological Society, Boston, 570-574.

TAF, 1995: Presentations at the peer review of the Tracking and Analysis Framework for the Office of Program Analysis of the Office of Energy Research of the U.S. Department of Energy, 18-19 December, 1995, Washington, D.C.

Trexler, E.C. Jr., and Laulainen, N., 1992: Techniques for computing and presenting annual visibility characterizations for locations of interest. In: *Proceedings of the 86th Annual Meeting,* Paper 93-RP-135.02, Air and Waste Management Association, Pittsburgh.

Trexler, E.C. Jr., and Shannon, J.D., 1995: The impact of climatological variability on visibility impairment distributions. In: *Proceedings of the International Specialty Conference on Aerosols and Atmospheric Optics: Radiative Balance and Visual Air Quality*, Snowbird, Utah, Sept. 26-30, 1994, Air and Waste Management Association, Pittsburgh, 681-692.

Trijonis, J.D., Malm, W.C., Pitchford, M., White, W.H., Charlson, R., and Husar, R., 1990: *Visibility: Existing and Historical Conditions - -Causes and Effects.* NAPAP Report 24, National Acid Precipitation Assessment Program, Washington, D.C.

Figure 1: Model comparisons with monitoring data for annual average concentration of atmospheric sulfate in the eastern United States in 1990 (micrograms per cubic meter).

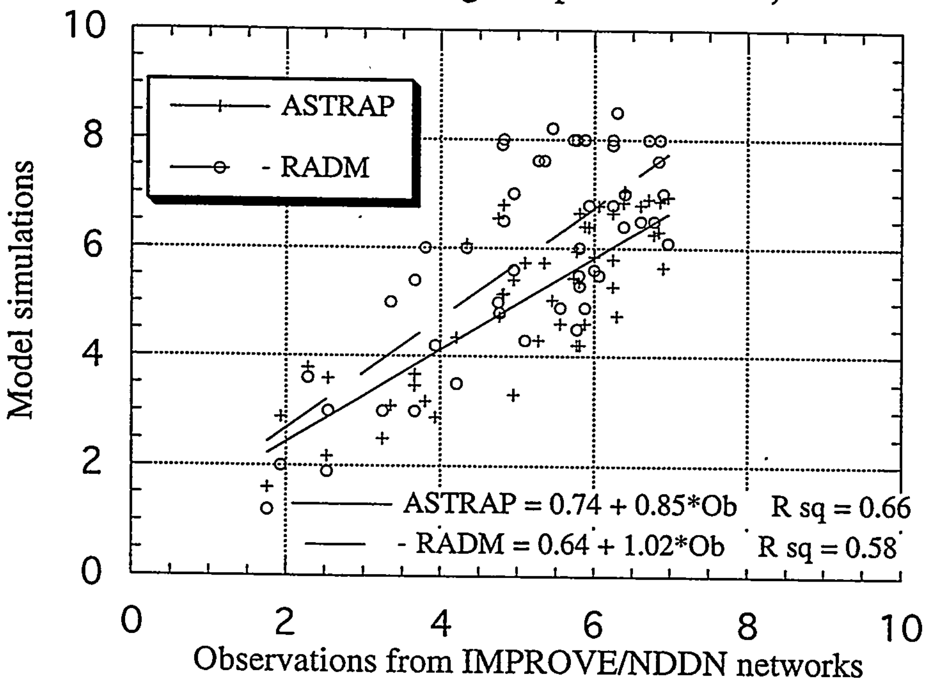

Figure 2a: Malm et al. optical extinction efficiencies.

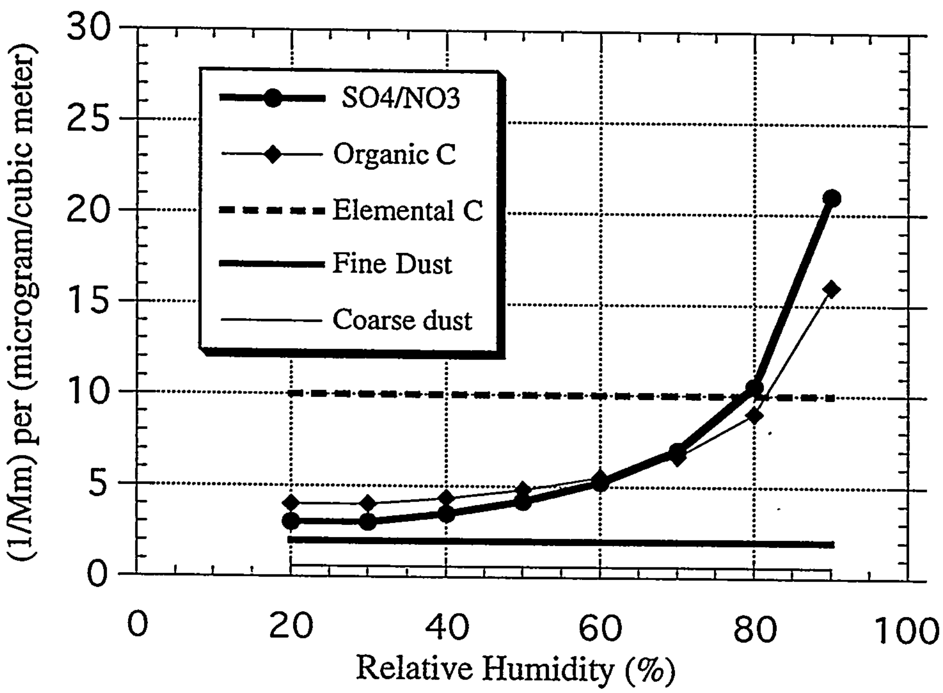

Figure 2b: McMurray-Lohenthal optical extinction efficiencies.

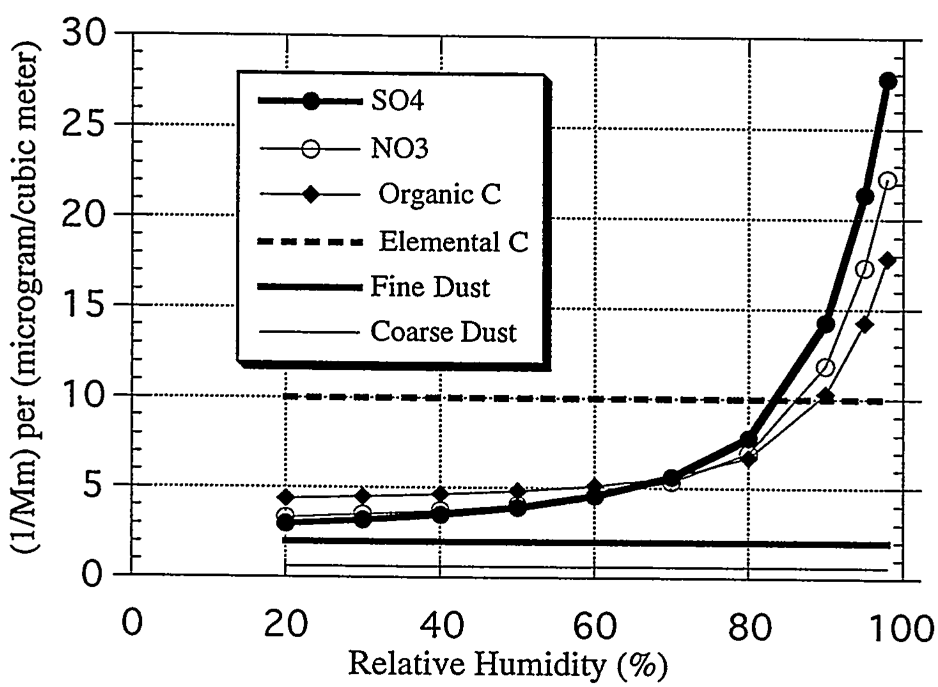

Figure 3a: Comparison of VASM simulations with observations of non weather-related visual impairment at Shenandoah National Park in winter.

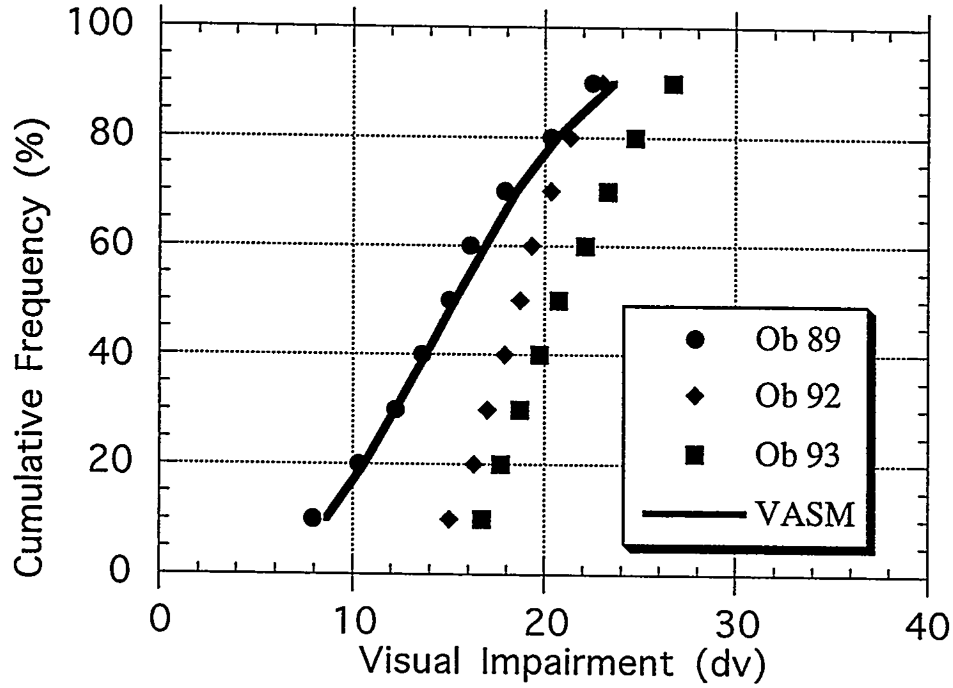

Figure 3b: Comparison of VASM simulations with observations of non weather-related visual impairment at Shenandoah National Park in spring.

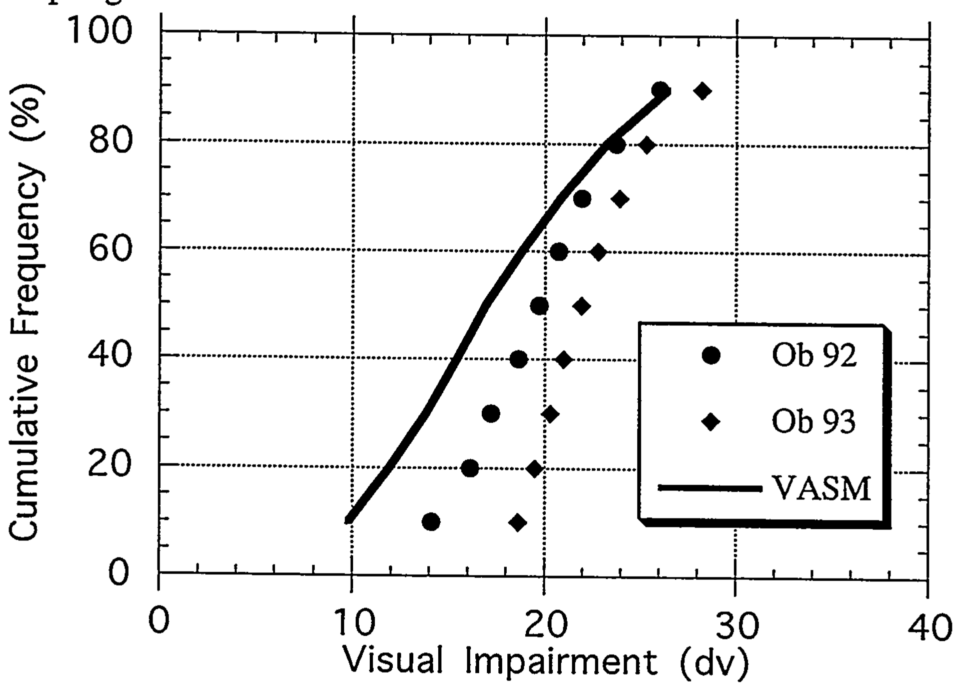

Figure 3c: Comparison of VASM simulations with observations of non weather-related visual impairment at Shenandoah National Park in summer.

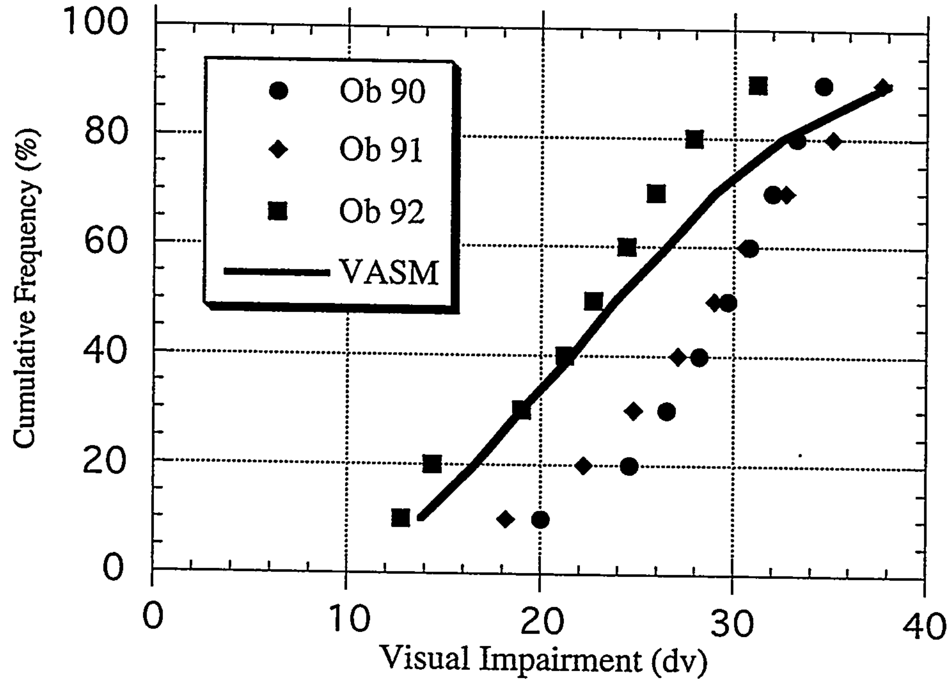

Figure 3d: Comparison of VASM simulations with observations of non weather-related visual impairment at Shenandoah National Park in autumn.

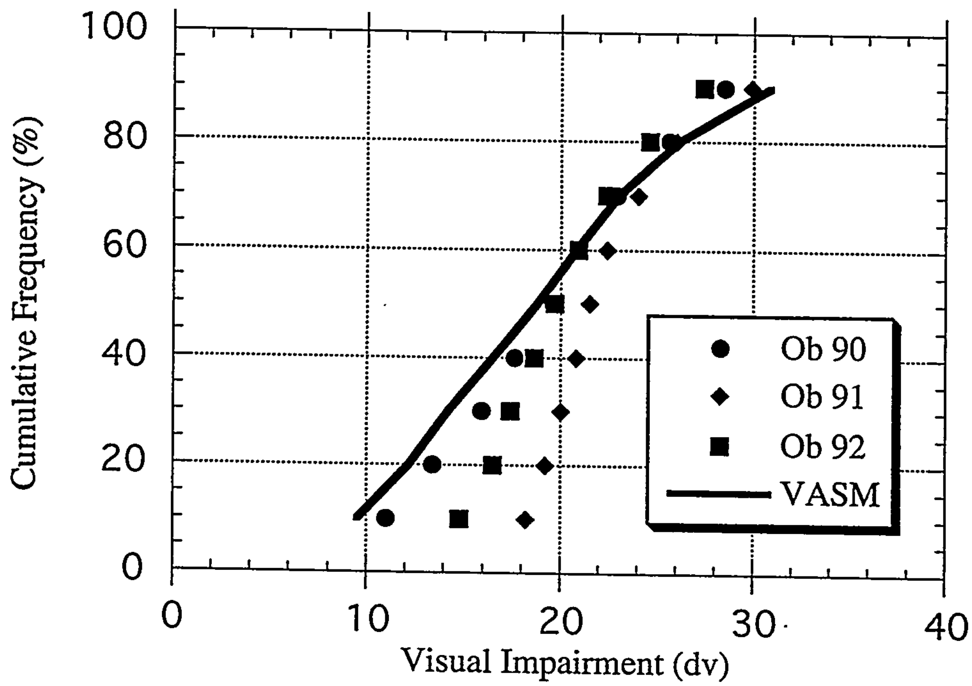

Figure 4a: Winter distribution of midday visual impairment at Shenandoah National Park before and after implementation of the SOx reductions of the 1990 Clean Air Act Amendments.

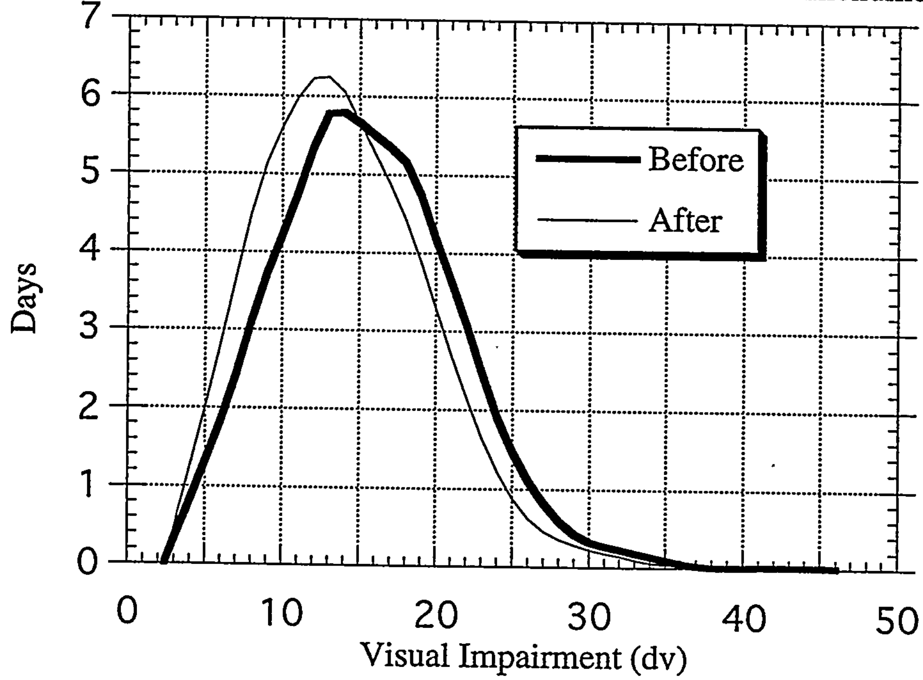

Figure 4b: Spring distribution of midday visual impairment at Shenandoah National Park before and after implementation of the SOx reductions of the 1990 Clean Air Act Amendments.

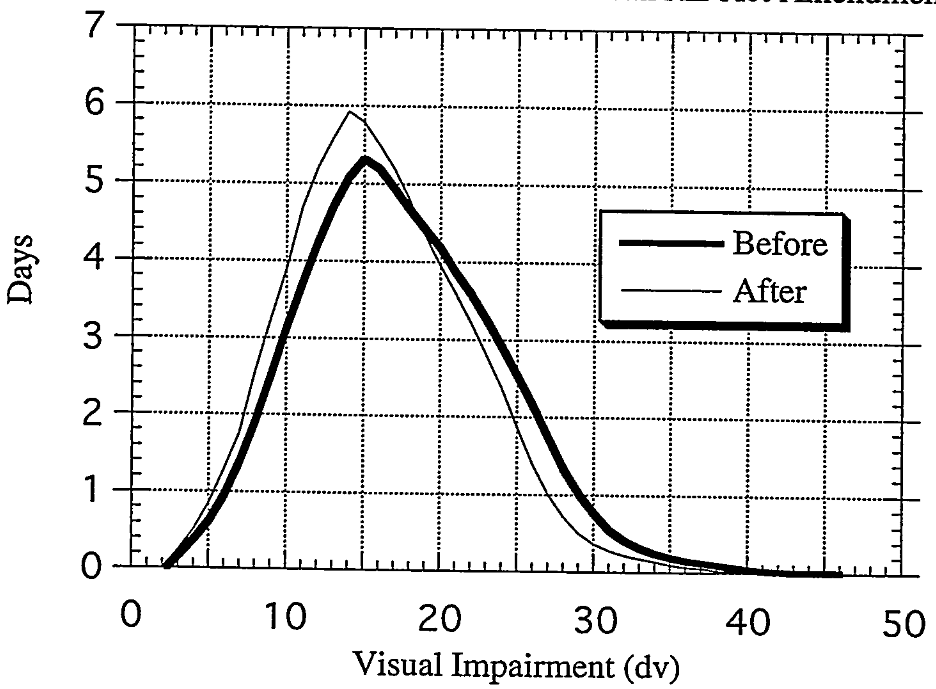

Figure 4c: Summer distribution of midday visual impairment at Shenandoah National Park before and after implementation of the SOx reductions of the 1990 Clean Air Act Amendments.

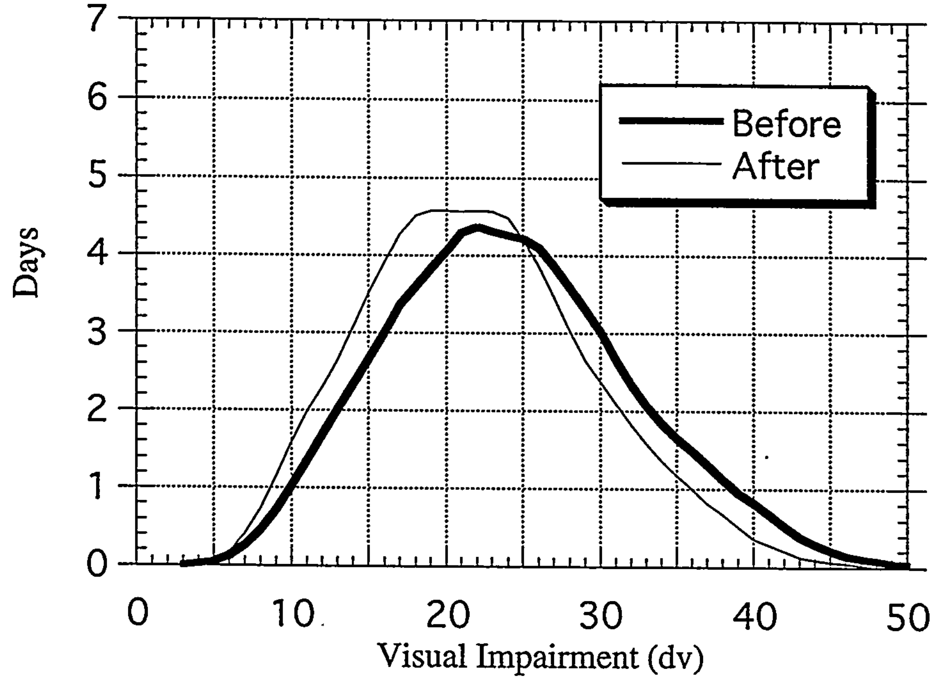

Figure 4d: Autumn distribution of midday visual impairment at Shenandoah National Park before and after implementation of SOx reductions of the 1990 Clean Air Act Amendments.