CHAPTER 6

Visibility Trends

http://www.epa.gov/oar/aqtrnd97/chapter6.pdf

INTRODUCTION

The Clean Air Act (CAA) authorizes the United States Environmental Protection Agency (EPA) to protect visibility, or visual air quality, through a number of programs. These programs include the national visibility program under sections 169A and 169B of the Act, the prevention of significant deterioration program for the review of potential impacts from new and modified sources, the secondary National Ambient Air Quality Standards (NAAQS) for PM_{10} and $PM_{2.5}$ and section 401 under the provisions for acid deposition control. The national visibility program established in 1980 requires the protection of visibility in 156 mandatory federal Class I areas across the country (primarily national parks and wilderness areas). The CAA established as a national visibility goal, "the prevention of any future, and the remedying of any existing, impairment of visibility in mandatory federal Class I areas in which impairment results from manmade air pollution." The Act also calls for state programs to make "reasonable progress" toward the national goal.

In 1987, the Interagency Monitoring of Protected Visual Environments (IMPROVE) visibility network was established as a cooperative effort between EPA, the National Oceanic and Atmospheric Administration, the National Park Service, the U.S. Forest Service, the Bureau of Land Management, the U.S. Fish & Wildlife Service, and State governments. The objectives of the network are to establish current conditions, to track progress toward the national visibility goal by documenting long-term trends, and to provide information for determining the types of pollutants and sources primarily responsible for visibility impairment. Chemical analysis of aerosol measurements provides ambient concentrations and associated light extinction for PM_{10}, $PM_{2.5}$, sulfates, nitrates, organic and elemental carbon, crustal material, and a number of other elements. The IMPROVE program has established protocols for aerosol, optical, and photographic monitoring methods, and these methods are employed at more than 70 sites, most of which are Class 1 areas. Over the next few years, an additional 78 monitoring sites using the IMPROVE protocol will be established. The analyses presented in this chapter are based on data from the IMPROVE network, which can be found on the Internet at: **ftp://alta_vista.cira.colostate.edu/DATA/IMPROVE**.[1]

This chapter presents aerosol and light extinction data collected between 1988 and 1997 at 37 Class I areas in the IMPROVE network. Because the CAA calls for the tracking of "reasonable progress" in preventing future impairment and remedying existing impairment, this analysis looks at trends in visibility impairment across the entire range of the visual air quality distribution. To facilitate this approach, visibility data have been sorted into quintiles, or 20 percent segments of the overall distribution, and average values have been calculated for each quintile. Trends are often presented in terms of the haziest ("worst") 20 percent, middle 20 percent, and clearest ("best") 20 percent of the annual distribution of data. Figure 6-1 provides a photographic illustration of very clear and very hazy conditions at Glacier National Park in Montana, and Dolly Sods Wilderness Area in West Virginia.[2] Figure 6-3 is a map of the 37 Class I areas with 6 or more years of IMPROVE monitoring data included in this analysis.

NATURE AND SOURCES OF THE PROBLEM

Visibility impairment occurs as a result of the scattering and absorption of light by particles and gases

Glacier National Park

Dolly Sods Wilderness

Figure 6-1. Images of Glacier National Park and Dolly Sods WA.

in the atmosphere. It is most simply described as the haze that obscures the clarity, color, texture, and form of what we see. The same particles linked to serious health and environmental effects (sulfates, nitrates, organic carbon, elemental carbon [commonly called soot], and crustal material) can also significantly affect our ability to see.

Both primary emissions and secondary formation of particles contribute to visibility impairment. Primary particles, such as elemental carbon from diesel and wood combustion or dust from certain industrial activities or natural sources, are emitted directly into the atmosphere. Secondary particles that are formed in the atmosphere from primary gaseous emissions include sulfate from sulfur dioxide (SO_2) emissions, nitrates from nitrogen oxide (NO_x) emissions, and organic carbon particles formed from condensed hydrocarbon emissions. In the eastern United States, reduced visibility is mainly attributable to secondarily formed particles, particularly those less than a few micrometers in diameter. While secondarily formed particles still account for a significant amount in the West, primary emissions from sources such as woodsmoke generally contribute a larger percentage of the total particulate load than in the East. The only primary gaseous pollutant that directly reduces visibility is nitrogen dioxide (NO_2), which can sometimes be seen in a visible plume from an industrial facility, or in some urban areas with high levels of motor vehicle emissions.

Visibility conditions in rural Class I areas vary regionally across the United States. Rural areas in the East generally have higher levels of impairment than most remote sites in the West. Higher eastern levels are generally due to higher regional concentrations of sulfur dioxide and other anthropogenic emissions, higher estimated regional background levels of fine particles, and higher average relative humidity levels. Humidity can significantly increase the effect of pollution on visibility. Some particles, such as sulfates, accumulate water and grow in size, becoming more efficient at scattering light. Annual average relative humidity levels are 70-80 percent in the East as compared to 50-60 percent in the West. Poor summer visibility in the eastern United States is primarily the result of high sulfate particle concentrations combined with high humidity levels.

Visibility conditions are commonly expressed in terms of three mathematically related metrics: visual range, light extinction, and deciviews. Visual range is the metric best known by the general public. It is the maximum distance at which one can identify a black object against the horizon, and is typically described in miles or kilometers. Light extinction, inversely related to visual range, is the sum of light scattering and light absorption by particles and gases in the atmosphere. It is typically expressed in terms of inverse megameters (Mm^{-1}), with larger values representing poorer visibility. Unlike visual range, the light extinction coefficient allows one to express the relative contribution of one particulate matter (PM) constituent versus another to overall visibility impairment. Using speciated mass measurements collected from the IMPROVE samplers "reconstructed light extinction" can be calculated by multiplying the aerosol mass for each constituent by its appropriate "dry extinction coefficient," and then summing these values for each constituent. Because sulfates and nitrates become more efficient at scattering light with increasing humidity, these values are also multiplied by a relative humidity adjustment factor.[3] Annual and seasonal light extinction values developed by this approach correlate well with optical measurements of light extinction (by transmissometer) and light scattering (by nephelometer).

The deciview metric was developed because changes in visual range and light extinction are not proportional to human perception. For example, a 5-mile change in visual range can be either very apparent or not perceptible, depending on the base line level of ambient pollution. The deciview metric provides a linear scale for perceived visual changes over the entire range of conditions, from clear to hazy, analogous to the decibel scale for sound. Under many scenic conditions, a change of one deciview is considered to be perceptible by the average person. A deciview of zero represents pristine conditions.

It is important to understand that the same amount of pollution can have dramatically different effects on visibility depending on existing conditions. Most importantly, visibility in cleaner environments is more sensitive to increases in $PM_{2.5}$ particle concentrations than visibility in more polluted areas. This principle is illustrated in Figure 6-2, which characterizes visibility at Shenandoah National Park under a range of conditions.[5] A clear day at Shenandoah can be represented by a visual range of 80 miles, with conditions approximating naturally-occurring visibility (i.e., without pollution created by human activities). An average day at Shenandoah is represented by a visual range of 18 miles, and is the result of an additional 10 g/m^3 of fine particles in the atmosphere. The two bottom scenes, with visual ranges of eight and six miles respec-

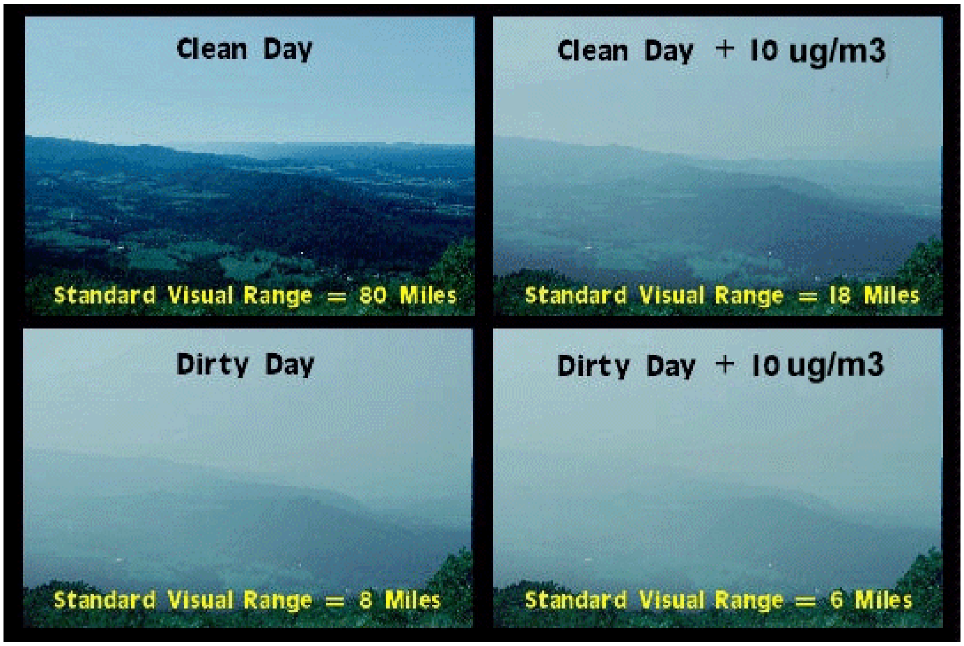


Figure 6-2. Shenandoah National Park on clear and hazy days and the effect of adding 10ug/m^3 of fine particles to each.

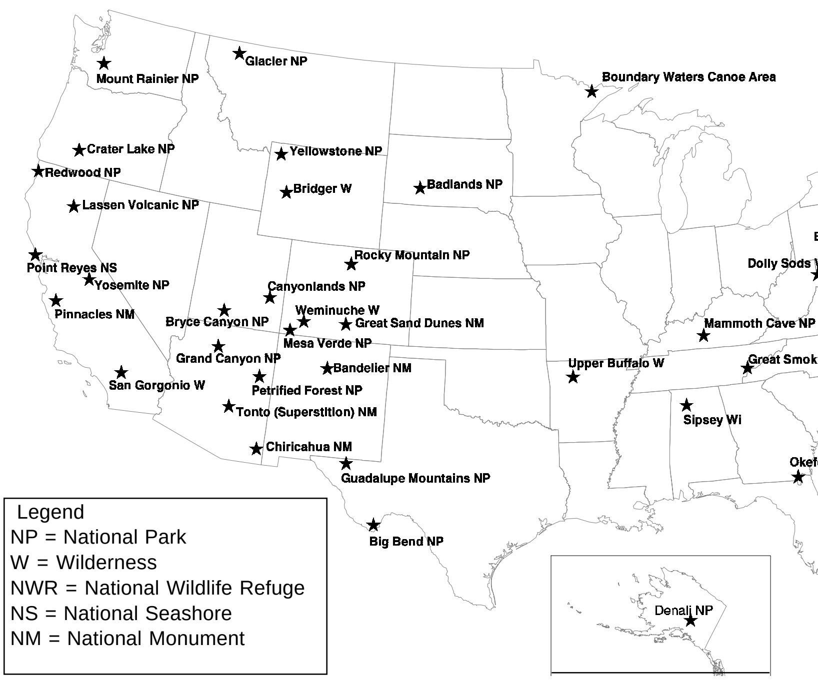


Figure 6-3. 37 Class I Areas in the IMPROVE Network with at least 6 years of data.

tively, illustrate that the perceived change in visibility due to an additional 10 g/m^3 of fine particles to an already degraded atmosphere is much less perceptible than adding this amount to a clean atmosphere. Thus, to achieve a given level of perceived visibility improvement, a larger reduction in fine particle concentrations is needed in more polluted areas. Conversely, a small amount of pollution in a clean area can dramatically decrease visibility.

LONG-TERM TRENDS

Visibility impairment is presented here using visual range data collected since 1960 at 280 monitoring stations located at airports across the country. Trends in visibility impairment can be inferred from these long-term records of visual range. Figure 6-4 describes long-term U.S. visibility impairment trends derived from such data.[4] The maps show the amount of haze during the summer months of 1970, 1980, and 1990. The dark blue color represents the best visibility, and red represents the worst visibility. Overall, these maps show that summer visibility in the eastern United States declined between 1970 and 1980, and improved slightly between 1980 and 1990. These trends follow overall trends in emissions of sulfur oxides during these periods.

RECENT TRENDS IN RURAL AREAS: 1988-1997

Aerosol and light extinction data have been collected for 10 consecutive years (1988-1997) at 30 sites in the IMPROVE network, and for 6 consecutive years (1992-1997) at 11 sites in the network. Of these 41 sites, 4 sites (Washington, D.C.; Bliss State Park, CA; Great Basin NP, NV; and Sequoia NP, CA) were omitted from the analyses in this chapter for reasons of missing data or location in an urban area. Washington, DC is the only urban location. The remaining 37 represent rural Class I areas: eleven are located in the East, and 26 are located in the West, as shown in Figure 6-3. Because of the significant regional variations in visibility conditions, this chapter does not present aggregate national trends, but instead groups the data into eastern and western regions. As noted earlier, trends in this chapter are frequently presented in terms of the annual average values for the clearest ("best") 20 percent, middle 20 percent , and haziest ("worst") 20 percent of the days monitored each year. To date, two 24-hour aerosol samples have been taken each week from IMPROVE sites, resulting in a potential for 104 sampling days per year. Beginning in 1999, aerosol samples will be taken every 3 days, consistent with the approach used for new $PM_{2.5}$ aerosol monitoring.

REGIONAL VISIBILITY TRENDS FOR THE EASTERN AND WESTERN UNITED STATES

Figures 6-5a and 6-5b illustrate eastern and western trends for total light extinction. These figures, presented with equivalent scales, demonstrate the regional difference in overall levels of visibility impairment. One can see that the worst visibility days in the west are only slightly more impaired than the best days in the East. It should also be noted that eight additional eastern sites are reflected in Figure 6-5a beginning in 1992, bringing to eleven the total number of eastern sites reflected in the values plotted in Figure 6-5a for 1992-97. By adding the 8 eastern sites to the dataset, the magnitude of average impairment levels has increased, although the general slope of the trends for clearest, middle, and haziest days appear similar to the trends based on three sites. Figure 6-5a shows that in the East, the haziest visibility days do not appear to be getting any better. Eastern impairment on the haziest days reached a low point in 1993, but both the 3- and 11- site trends have increased by about 4% by 1997. The best visibility days appear to be relatively flat or improving slightly. The middle 20 percent of the distribution appears to have a downward trend exceeding 10 percent for both the 3-sites and 11-site lines.

In the West, there appears to be steady visibility improvement in each of the 3 quintiles presented in Figure 6-5b for the period 1988-1997. Total light extinction for the aggregation of 26 western sites declined by 11-14 percent for each of the 3 categories. In the East, the average deciview value for the worst visibility days increased by about 0.5, while in the West, the average value decreased by 1.5 deciviews.

The area plots in Figures 6-6a through 6-6f show the relative contribution to aerosol light extinction

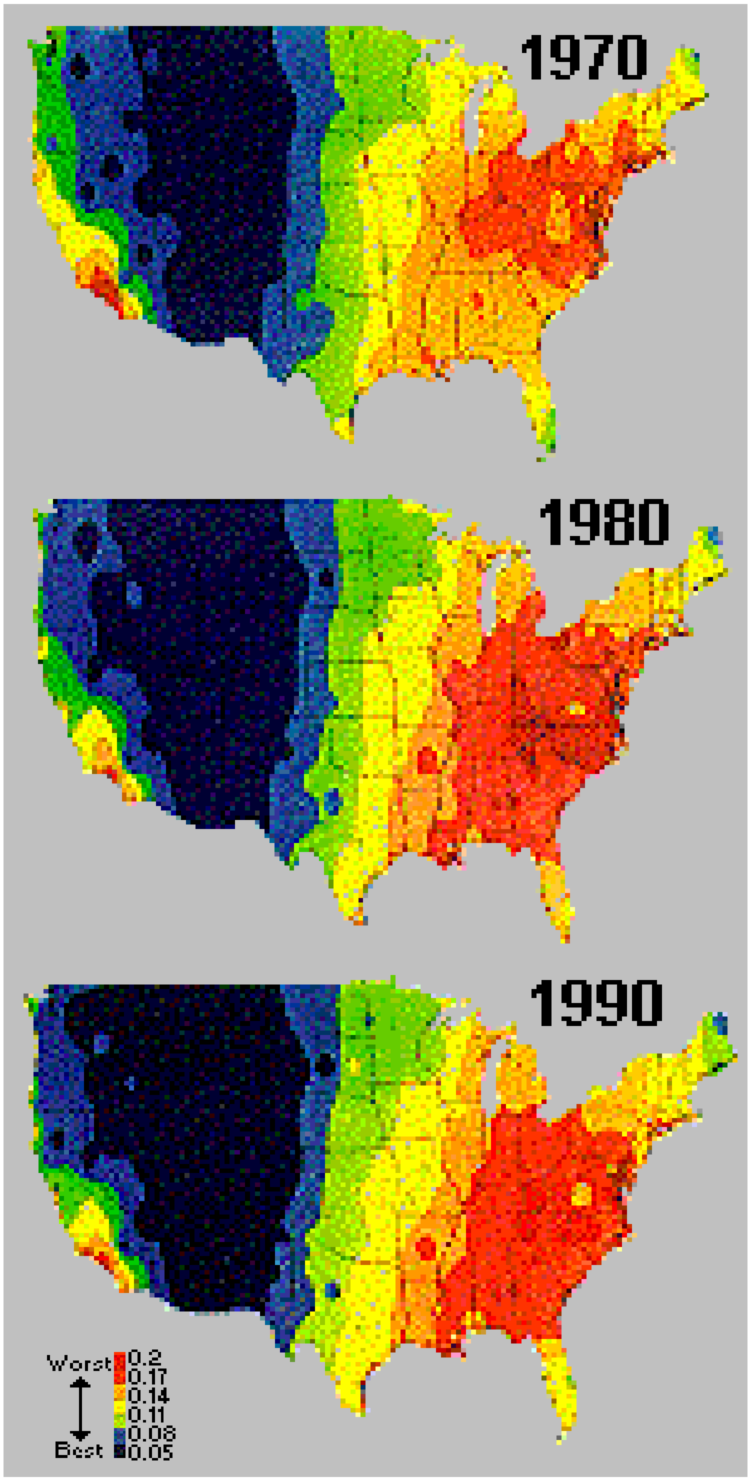


Figure 6-4. Long-term trend for 75th percentile light coefficient from airport visual data (July-September).

by the five principal particulate matter constituents measured by IMPROVE at eastern and western sites for the best, middle, and worst 20 percent days. Note that the scale differs for the eastern and western figures in order to more clearly present the relative contribution of the five components. By understanding the total magnitude of each $PM_{2.5}$ component, the change in aerosol composition over time, and the effect of these components on changing visibility, policymakers can design strategies to address health and environmental concerns.

In the East, (Figures 6-6a, b, and c), sulfate is clearly the largest contributor to visibility impairment, ranging from 64 percent of aerosol extinction during the best days to 80% on the worst days. Since reaching a low point in 1993, light extinction due to sulfate has increased slightly about 7 percent by 1997. Organic carbon is the next largest contributor to visibility impairment in the East, accounting for 12 percent of aerosol extinction on the best days and averaging 9 percent on the most impaired days. Over the period 1992-1997, the contribution of organic carbon to aerosol light extinction appears to be declining for the clearest, middle, and haziest days. The third largest contributor in the East is nitrate, which also accounts for about 12 percent of aerosol light extinction on the best days and about 5 percent on the haziest days.

In the West, sulfate is also the most significant single contributor to aerosol light extinction on the best, middle, and worst 20 percent days of the distribution. Sulfate typically accounts for 35-45 percent of aerosol light extinction. However, organic carbon (19-22 percent), crustal material (16-20 percent), and nitrates (12-15 percent) play a more significant role (as a percentage of aerosol extinction) in western sites than eastern ones. Based on this aggregation of 26 sites, it appears that organic carbon and elemental carbon are showing downward trends in western Class I areas.

Trends in Specific Class I Areas

IMPROVE data from 37 Class I area monitoring sites (29 with data for 1988-1997, 8 with data for 1992-1997) were analyzed for upward or

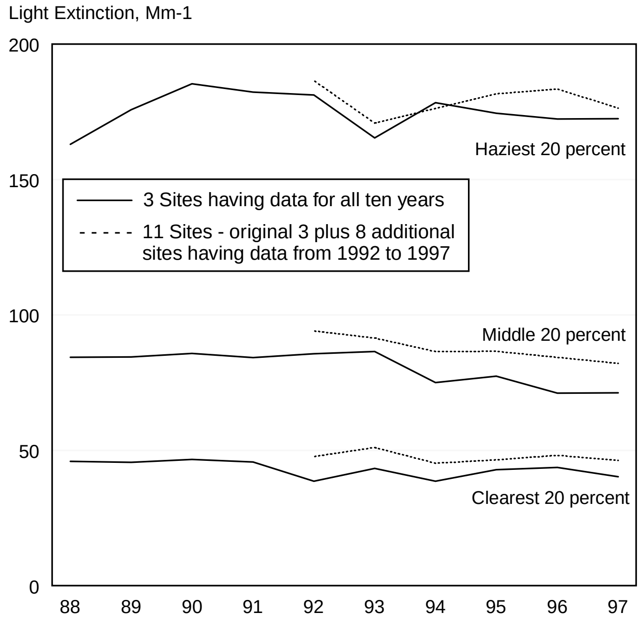


Figure 6-5a. Total light extinction trends for eastern Class I areas for haziest, middle, and clearest 20 percent of the distribution, 1988-1997.

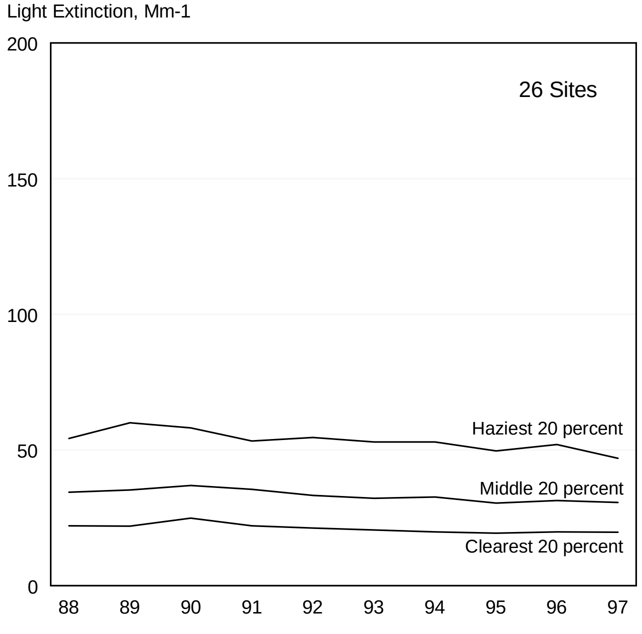


Figure 6-5b. Total light extinction trends for western Class I areas for haziest, middle, and clearest 20 percent of the distribution, 1988-1997.

downward trends using a nonparametric regression methodology described in Chapter 3: Criteria Pollutants - Metropolitan Area Trends.

Table 6-1 summarizes the trends analysis performed on these 37 sites for total light extinction (expressed in deciviews), light extinction due to sulfate, and light extinction due to organic carbon.

Overall, about one-fourth of the sites showed a significant downward trend in deciviews on the worst days, and more than one-third of the sites exhibited a significant improvement in visibility on the best days. Only a few sites showed a significant downward trend for light extinction due to sulfate, whereas one-half to three-fourths of the sites demonstrated significant improvements in light extinction due to organic carbon. Two sites were found to have statistically significant upward trends for the 9 parameters presented: Badlands National Park (SD) showed a significant upward trend in deciviews for the worst days, and San Gorgonio Wilderness (CA) showed a significant positive trend for light extinction due to sulfate. Several other sites also had positive slopes for various parameters, indicating some degree of an upward trend. A review of the annual data plotted

Figure 6-6a. Aerosol light extinction in eastern Class I areas for the clearest 20 percent of the distribution, 1988-1997.

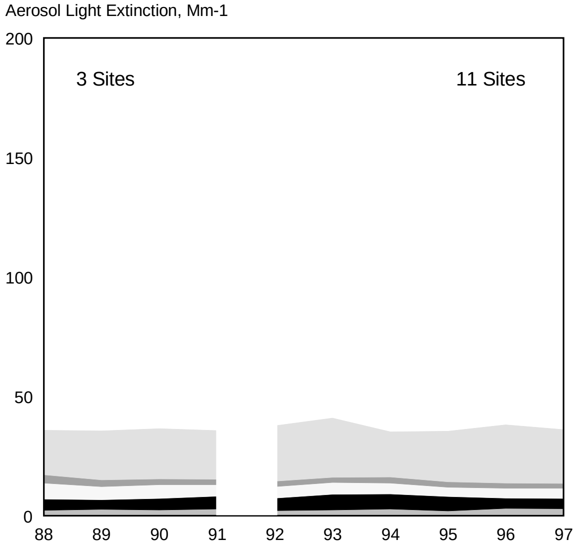


Figure 6-6b. Aerosol light extinction in eastern Class I areas for the middle 20 percent of the distribution, 1988-1997.

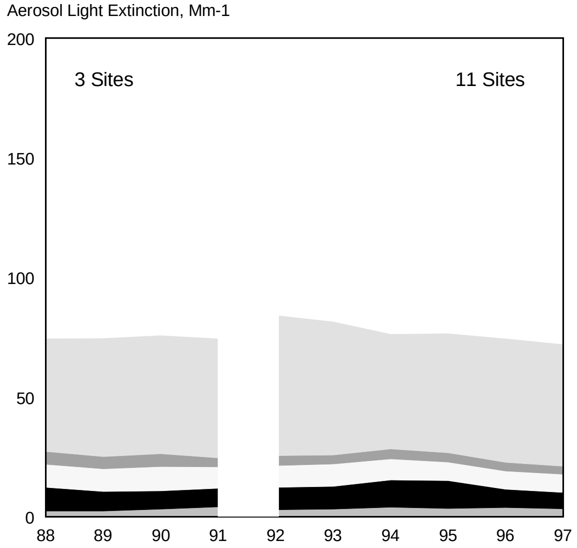
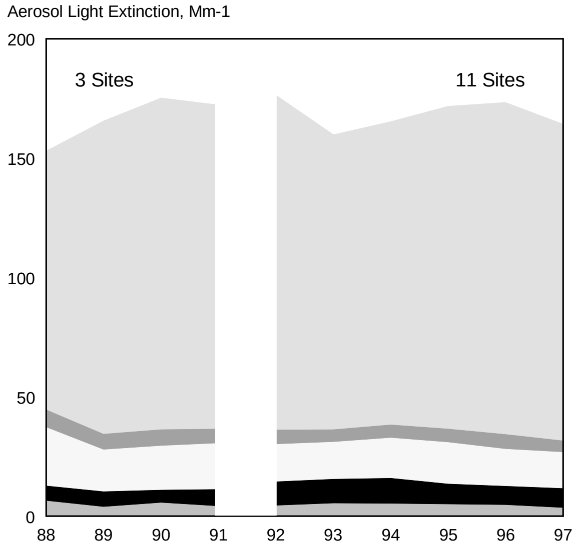


Figure 6-6c. Aerosol light extinction in eastern Class I areas for the haziest 20 percent of the distribution, 1988-1997.



Notes:

1) To better discern the trend in each component, the vertical scales for the plots of the Western Class I areas are smaller than those for the plots of the Eastern Class I areas.

2) In the Eastern Class I area plots, the 1988-1991 trend is based on the 3 sites with available data. Beginning in 1992 and going through 1997, there are 8 additional sites with trend data.

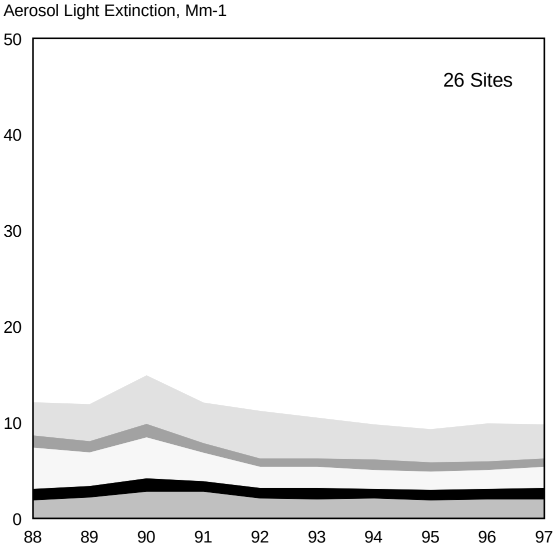


Figure 6-6d. Aerosol light extinction in western Class I areas for the clearest 20 percent of the distribution, 1988-1997.

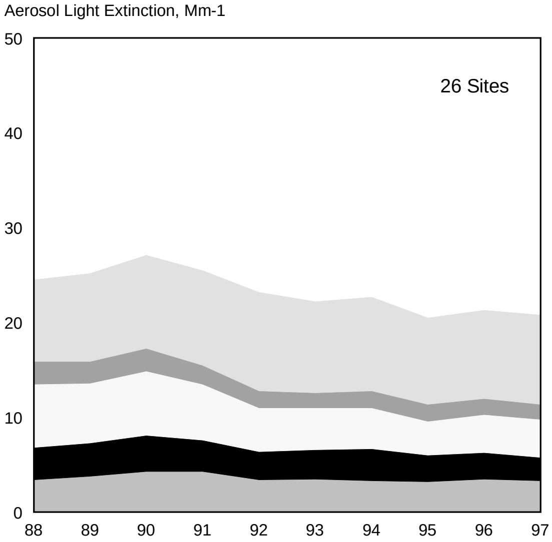


Figure 6-6e. Aerosol light extinction in western Class I areas for the middle 20 percent of the distribution, 1988-1997.

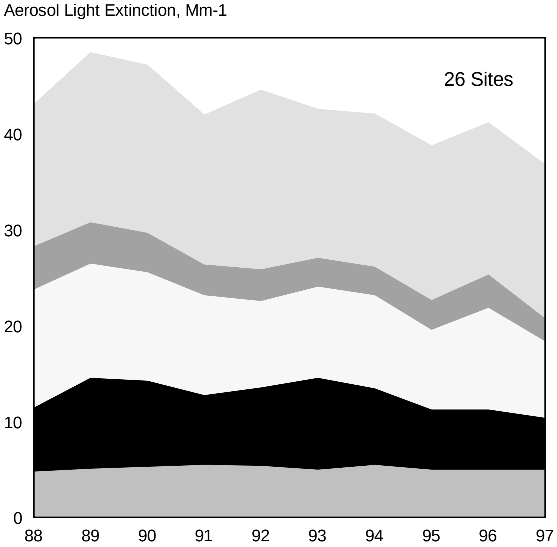


Figure 6-6f. Aerosol light extinction in western Class I areas for the haziest 20 percent of the distribution, 1988-1997.

for each site as well as the results from the nonparametric regression method described in Chapter 3 shows that several sites have positive slopes and should be monitored closely for potential upward trends for either the best, middle, or worst 20 percent of the days in the distribution. Table 6-2 lists those sites which may be of potential concern.

CURRENT CONDITIONS

Current annual average conditions range from about 18-40 miles in the rural East and about 35-90 miles in the rural West. On an annual average basis, natural visibility conditions have been estimated at approximately 80-90 miles in the East and up to 140 miles in the West.[5] Natural visibility varies by region primarily because of slightly higher estimated background levels of $PM_{2.5}$ particles in the East, and the more significant effect of relative humidity on particle concentrations in the East than in the West.

Figures 6-7a, 6-7b, and 6-7c illustrate regional visibility impairment in terms of reconstructed aerosol light extinction based on measurements at IMPROVE sites between 1995 and 1997. Maps are presented for the clearest, middle and haziest 20 percent of the distribution. The pie charts show the relative contribution of different particle constituents to visibility impairment. Annual average aerosol light extinction due to these particles is indicated by the value next to each pie and by the size of each pie.[6] Figure 6-7 also shows that visibility impairment is generally greater in the rural East compared to most of the West. As not-

Table 6-1. Summary of Class I Area trend* analysis.

Parameter	Number of Sites With Significant Upward (**Deteriorating**) Trends		Number of Sites With Significant Downward (**Improving**) Trends	
	West	**East**	**West**	**East**
Deciviews, worst 20%	1	0	9	0
Deciviews, middle 20%	0	0	15	3
Deciviews, best 20%	0	0	11	2
Light extinction due to sulfate, worst 20%	0	0	0	0
Light extinction due to sulfate, middle 20%	0	0	0	3
Light extinction due to sulfate, best 20%	1	0	2	0
Light extinction due to organic carbon, worst 20%	0	0	15	1
Light extinction due to organic carbon, middle 20%	0	0	24	5
Light extinction due to organic carbon, best 20%	0	0	22	5

* Based on a total of 37 monitored sites with at least 6 years of data: 26 in the West, 11 in the East.

ed earlier, sulfates account for more than 60 percent of annual average light extinction at most rural eastern sites. Sulfate plays a particularly significant role in the humid summer months due to its nature to attract and dissolve in atmospheric water vapor, most notably in the Appalachian, northeast, and mid-south regions. Nitrates, organic carbon, and elemental carbon all account for between 10-15 percent of total light extinction in most Eastern locations.

In the rural West, sulfates also play a significant role, typically accounting for about 25-40 percent of total light extinction in most regions. In several areas of the West, however, Sulfates account for over 50 percent of annual average light extinction, including Mt Rainier, WA, Point Reyes, CA, Redwood NP, CA, and the Cascades of Oregon. Organic carbon typically makes up 15-35 percent of total light extinction in the rural West, elemental carbon (absorption) accounts for about 15-25 percent, and soil dust (coarse PM) accounts for about 10-20 percent. Nitrates typically account for less than 10 percent of total light extinction in western locations, except in the southern California region, where it accounts for almost 40 percent.

Figures 6-8a, 6-8b, and 6-8c illustrate current levels of visibility impairment, in terms of deciviews, for the clearest, middle, and haziest 20 percent days based on IMPROVE data from 1995-1997.[7] Note that the deciview scale is more compressed than the scale for visual range or light extinction, with larger values representing greater visibility degradation. Most of the sites in the intermountain West and Colorado Plateau have annual average impairment of 12 deciviews or less, with the worst days ranging up to 16 deciviews. Several other western sites in the northwest and California experience levels on the order of 15-25 deciviews on the haziest 20 percent of days. Many rural locations in the East have annual aver-

Table 6-2. Class I areas with potentially deteriorating visibility (based on trend in deciviews).

Clearest 20% Days	Middle 20% Days	Haziest 20% Days
Brigatine Wilderness (NJ) Dolly Sods wilderness (WV) Lye Brook Wilderness (VT) Okefenokee Wilderness (FL) San Gorgonio Wilderness (CA)	Lye Brook Wilderness (VT) Upper Buffalo Wilderness (AR)	Badlands NP (SD) Bandelier National Monument (NM) Big Bend NP (TX) Bryce Canyon NP (UT) Great Smokies NP (TN) Mammoth Cave NP (KY) Shenandoah NP (VA) Sipsey Wilderness (AL)

Figure 6-7a. Aerosol light extinction (in Mm-1) for the clearest 20% days and contribution by individual particulate matter constituents, based on 1995-1997 IMPROVE data.

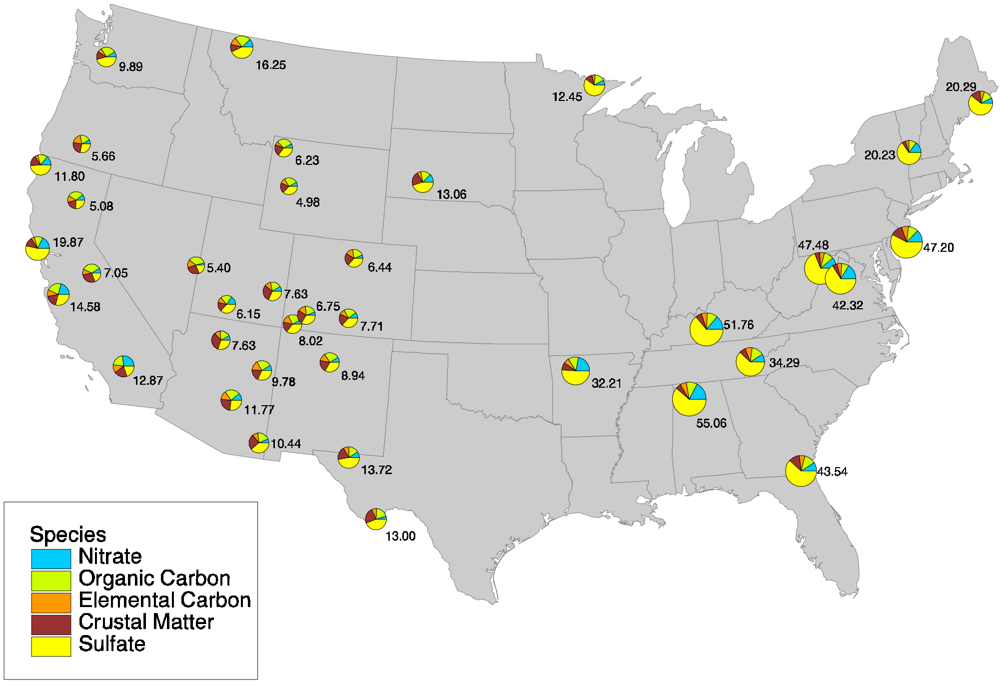


Figure 6-7b. Aerosol light extinction (in Mm-1) for the middle 20% days and contribution by individual particulate matter constituents, based on 1995-1997 IMPROVE data.

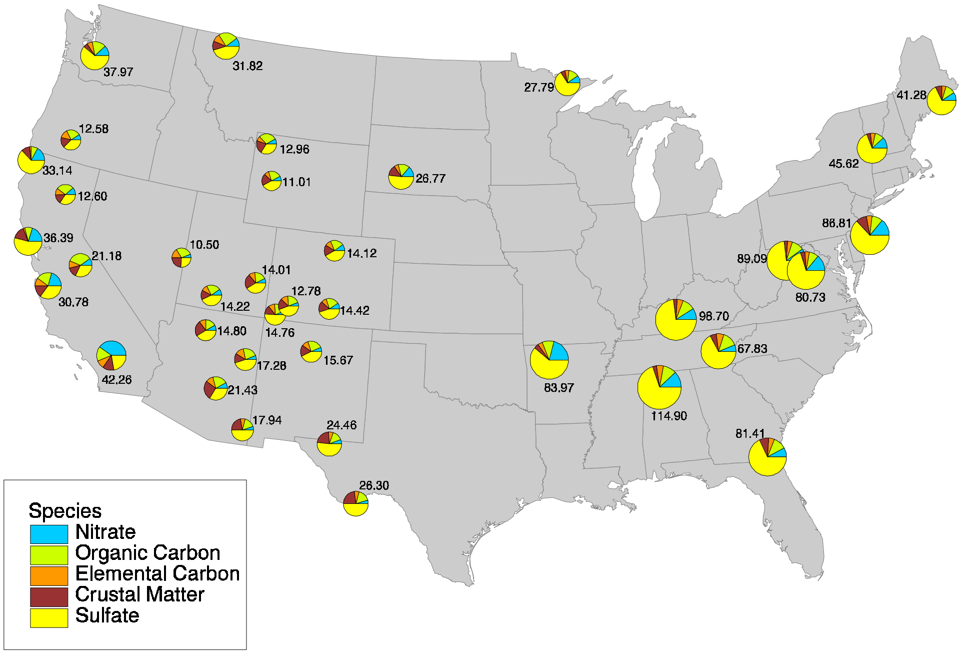


Figure 6-7c. Aerosol light extinction (in Mm-1) for the haziest 20% days and contribution by individual particulate matter constituents, based on 1995-1997 IMPROVE data.

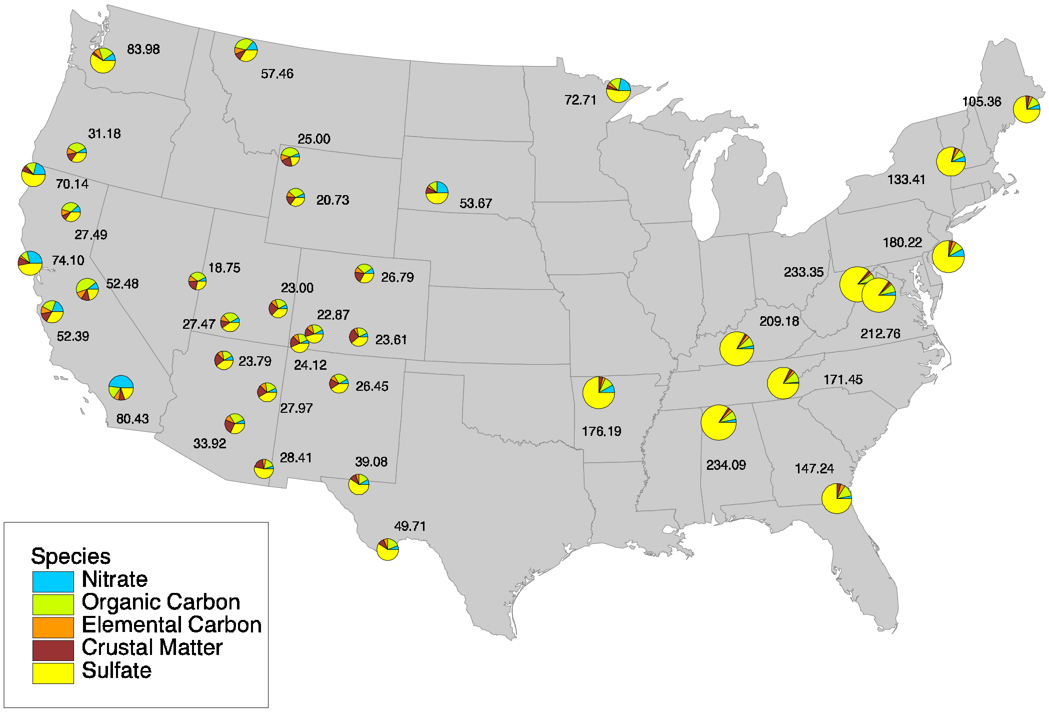


Figure 6-8a. Current visibility impairment expressed in deciviews for the clearest 20% days based on 1995-1997 IMPROVE data.

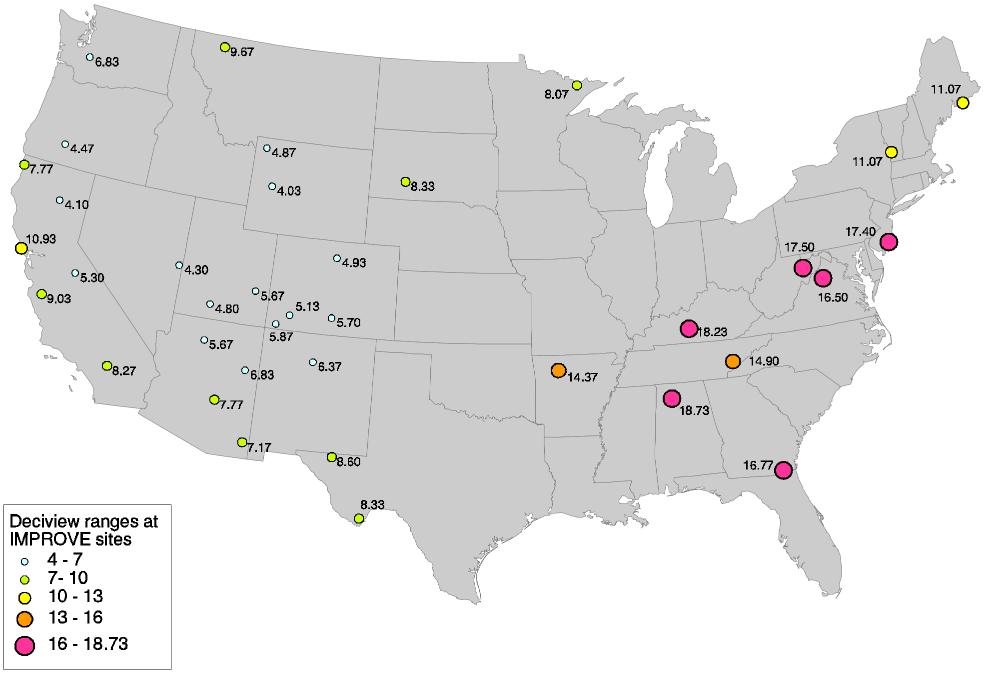


Figure 6-8b. Current visibility impairment expressed in deciviews for the middle 20% days based on 1995-1997 IMPROVE data.

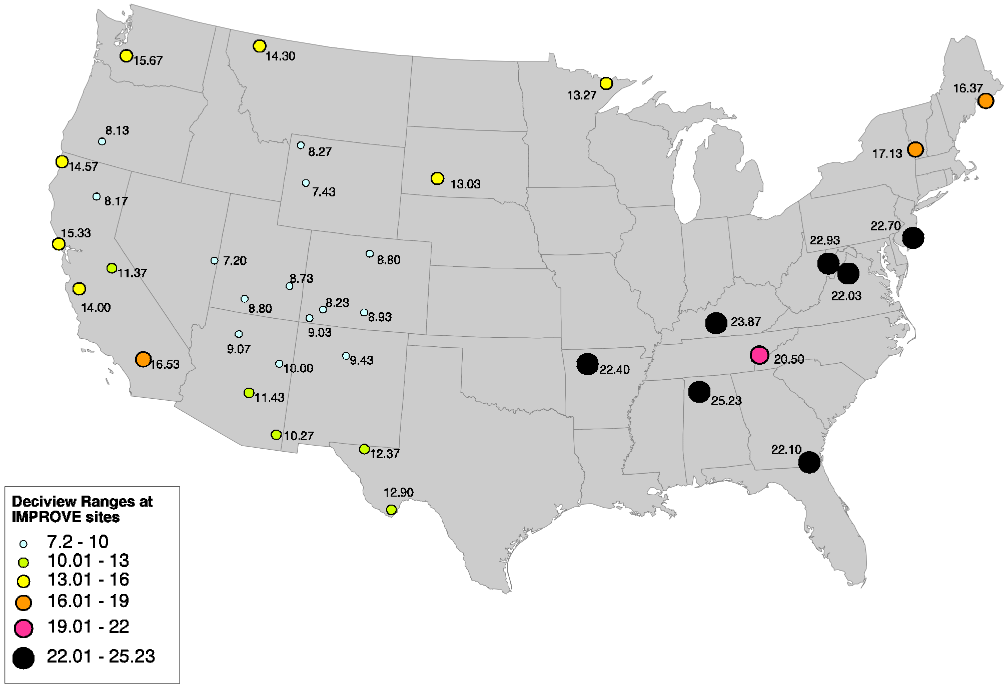
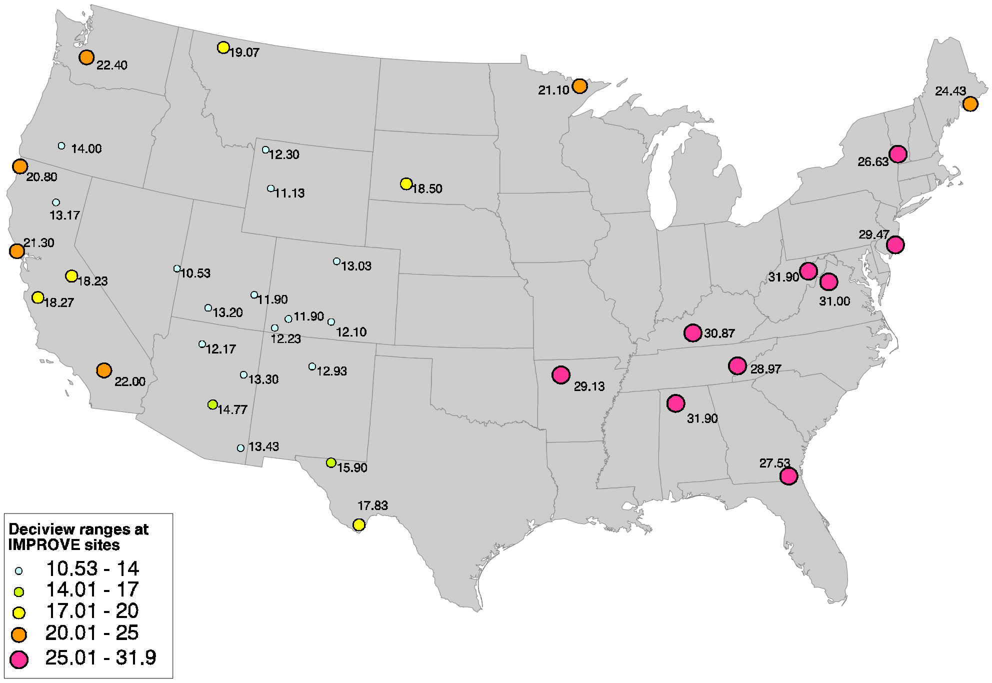


Figure 6-8c. Current visibility impairment expressed in deciviews for the haziest 20% days based on 1995-1997 IMPROVE data.



age values exceeding 23 deciviews, with average visibility levels on the haziest days up to 33 deciviews.

PROGRAMS TO IMPROVE VISIBILITY

In July 1997, EPA proposed a new regional haze program to address visibility impairment in national parks and wilderness areas caused by numerous sources located over broad regions. The proposed program takes into consideration scientific findings and policy recommendations from a number of sources, including the National Academy of Sciences, the Grand Canyon Visibility Transport Commission, and a Federal Advisory Committee on Ozone, Particulate Matter, and Regional Haze Implementation Programs. The proposal lays out a framework within which states can conduct regional planning and develop implementation plans which are to achieve "reasonable progress" toward the national visibility goal of no human-caused impairment in the 156 mandatory Class I federal areas across the country. Because of the common precursors and the regional nature of the ozone, PM, and regional haze problems, EPA is developing these implementation programs together to integrate future planning and control strategy efforts to the greatest extent possible. Implementation of the PM and Ozone NAAQS in conjunction with a future regional haze program is expected to improve visibility in urban as well as rural areas across the country. Other air quality programs are expected to lead to emissions reductions that will improve visibility in certain regions of the country. The acid rain program will achieve significant regional reductions in the emissions of SO_2, which is expected to reduce sulfate haze particularly in the eastern United States. The recent NO_x State Implementation Plan (SIP) call to reduce emissions from sources of NO_x to reduce formation of ozone should also improve regional visibility conditions to some degree. In addition, the NAAQS, mobile source, and woodstove programs to reduce fuel combustion and soot emissions can benefit areas adversely impacted by visibility impairment due to sources of organic and elemental carbon.

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6. See reference 1.

7. See reference 1.