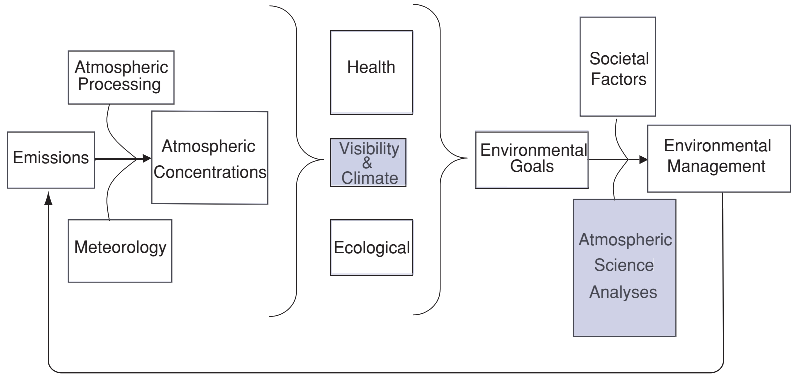
CHAPTER 9

Visibility and Radiative Balance Effects



Principal Authors: Ivar Tombach and Karen McDonald

In addition to their effects on human health, particles in the atmosphere contribute to impairment of visibility and affect the global radiation balance (which, in turn, affects climate). These effects are governed by the atmospheric concentrations of particles, their spatial distribution (both geographically and vertically), and their size distribution and chemical composition. Thus all of the factors discussed in Chapters 3 through 8 are of relevance for understanding and managing visibility impairment and radiative-balance effects due to particles. This chapter addresses the linkage between PM and visibility and radiative-balance effects, as well as additional issues unique to visibility and radiative balance. The principal focus here is on visibility impairment, which is closely linked to PM concentrations and composition. The radiative-balance effects of PM, which are only one component of climate change due to air pollution, are discussed in less detail.

9.1 HOW IS VISIBILITY LINKED TO PM?

Particles suspended in the air interfere with the transmission of light through the atmosphere. The scattering and absorption of light by the particles result in a degradation of visibility, which is manifested as a reduction in the distance to which one can see and a decrease in the apparent contrast and color of distant objects. Furthermore, the particles may scatter sunlight into the image, causing a washed-out appearance, or the atmosphere itself may have a hazy appearance that has different color and brightness than a haze-free atmosphere. These processes are illustrated in Figure 9.1.

To the public, these optical effects are the most readily recognized indications of the presence of particulate air pollution. Visibility is also affected by natural clouds and fog and by precipitation, but the focus here is on visibility effects resulting from air-pollutant particles.

Visibility is concerned with the propagation of light in the horizontal direction. The same processes of atmospheric light scattering and absorption also occur in the vertical direction and affect the balance between the light and heat that reaches the earth from the sun and that which is propagated back into space. The impacts of particles on this radiation balance influence weather and climate, as discussed briefly later in this chapter.

Visibility effects due to particulate air pollution take place over two spatial scales: local and widespread. Localized plumes or clouds of pollution can obscure visibility, a process that is sometimes called plume blight. Because of the short travel time of a plume from a nearby source, local visibility effects are usually caused mostly by primary particles. Widespread pollution can produce a regional haze that extends over distances of tens or hundreds of kilometers. Many sources distributed over a wide area may contribute to regional haze and, because of the longer transport times (typically over many hours or a few days), regional haze is usually caused mostly by secondary particles.

Physical linkages exist between PM concentrations and visibility effects. Increasing concentrations of PM result in roughly proportional increases in the amount of light that is scattered and absorbed by the particles. Increasing relative humidity also increases the amount of light that is scattered relative to that of

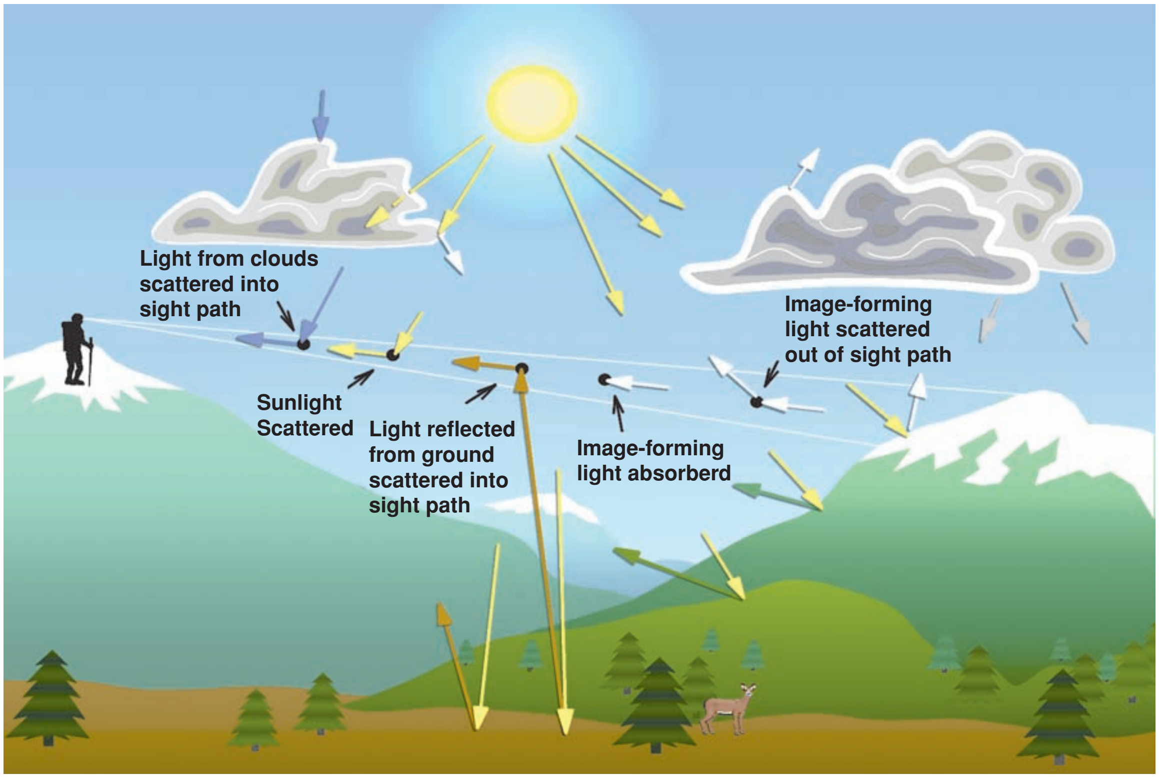


Figure 9.1. Illustration of the three processes by which particles and gases in the atmosphere affect visibility– the scattering of image-forming light, the absorption of image-forming light, and the scattering of light into the sight path. (Adapted from Malm, 2000a).

dry PM. In most cases in ambient air, the scattering of light by particles is much greater than the absorption of light by either particles or gases. In some urban areas and major point-source plumes, however, absorption by soot particles and/or by NO_2 gas can be important. The combined effect of light scattering and absorption, due to both particles and gases, is called light extinction and is characterized by the extinction coefficient. For any given scene and illumination condition, an increase in the extinction coefficient is associated with a decrease in visibility. Visibility can be defined in terms of the distance one can see (the visual range), which is inversely proportional to the extinction coefficient. (For additional discussion of the optical effects of particles, see Watson (2002), Malm (2000a), NRC (1993), and Trijonis et al. (1990).)

The extinction coefficient, denoted b_{ext}, is a measure of the fraction of light that is lost from a beam of light as it traverses a unit distance through a uniform atmosphere. Formally, for a beam of light with initial intensity I_0, its intensity after passing through a distance r of atmosphere with extinction coefficient b_{ext} is $I = I_0 \exp(-b_{ext}\, r)$.

For example, the extinction coefficient of particle-free air (the Rayleigh scattering coefficient) at sea level is 0.012 km^{-1} for light at the peak wavelength of human sensitivity. This means that 1.2 percent of the light in the beam is lost (scattered by air molecules) as the beam passes through one kilometer of a clean atmosphere. For convenience, a megameter, denoted Mm and equal to 1000 km, is often used as the unit of distance, in which case the sea level Rayleigh scattering coefficient is 12 Mm^{-1}. The corresponding visual range along a path that follows the earth's surface would be about 325 km, were it possible to see around the curvature of the earth.

This Rayleigh scattering by air molecules can make up the majority of the light extinction on the clearest days in arid, relatively unpopulated areas, such as the intermountain region of the western United States and Canada, and in the Arctic. On less clear days and elsewhere, scattering and absorption by PM dominate the light extinction.

The light-extinction effects of PM vary with particle size and chemical composition. The particles with the greatest influence on visibility are fine particles of the same scale as the wavelengths of visible light (approximately 0.3 to 1 µm in diameter), which are composed primarily of $SO_4^=$, NO_3^-, OC, and BC. Fine soil particles and coarse particles of all compositions usually play much smaller roles, except in areas where wind-blown dust is a factor. Because particle sizes and compositions depend on the natures of the sources that emit the particles or their precursors, emissions from different sources will have different effects on visibility. Thus, although reducing ambient concentrations of PM will also yield benefits in visibility, the most effective approach to managing visibility may differ from the optimum one for the management of PM mass concentrations to protect human health at the same location.

9.1.1 How Is Visibility Distributed and How Has It Varied over the Years?

As was shown in Chapter 6, PM due to man's emissions is present to some degree over all of North America most of the time. As a result, visibility impairment caused by air pollution is not limited to cities with substantial PM pollution, such as Los Angeles and Mexico City, but is also present in rural and remote areas (even the high Arctic). The U.S. National Research Council reports that visibility impairment caused by air pollution occurs in varying degrees at many U.S. national parks virtually all of the time (NRC, 1993).

Extensive measurements of the fine PM species that cause light extinction have been carried out in rural areas of the United States for the past decade. Figure 9.2 shows the distribution of average light extinction over the United States, calculated from particle measurements made by the IMPROVE (Interagency Monitoring of Protected Visual Environments) network at national parks and wilderness areas. (The

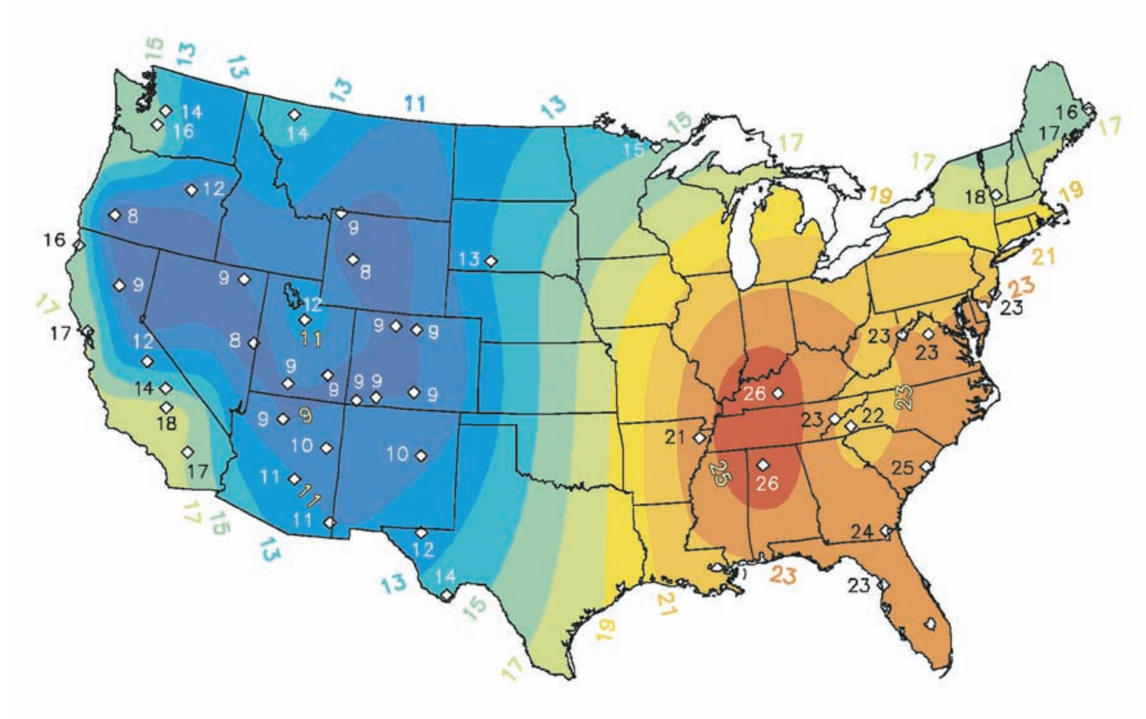


Figure 9.2. Distribution of average light extinction in national parks and wilderness areas of the United States, in units of deciviews, as calculated from particulate matter measurements in the IMPROVE network (Malm, 2000b).

methodology used for such calculations will be described below in Section 9.1.3.) This figure shows the dramatic difference between the relatively impaired visibility in the more humid and more populated East and the much clearer visibility in the arid and relatively unpopulated intermountain West. Visibility along the Pacific Coast is again poorer because of increased population density and, in the Northwest, higher humidity. Urban areas normally have greater PM concentrations and thus the average visibility there can be expected to be worse than that shown in Figure 9.2.

Figure 9.2 presents extinction in units of deciviews. The deciview (Pitchford and Malm, 1994) has come into vogue recently for representing extinction because a given increment in deciviews is assumed to be perceived approximately the same by a human observer, independent of the absolute level of extinction. For example, a change by 2 dV is assumed to be perceived similarly whether the original extinction is 5 dV or 25 dV. In analogy with the decibel scale for hearing, the formula for deciviews is $dV = 10 \ln(b_{ext}/10)$, where b_{ext} is in units of Mm^{-1}. Zero dV corresponds to Rayleigh scattering at an altitude of about 1500 m, and increasing values of the deciview index represent increasing light extinction, i.e., decreasing visibility. A difference of 1 dV corresponds to a difference of about 10 percent in the extinction coefficient.

Canada has a similar east-to-west spatial pattern of visibility as the United States. Figure 9.3 illustrates light extinction statistics averaged over Canadian regions, based on fine PM speciation measurements made in urban areas (McDonald, 2002). (Recall that Figure 9.2 represents rural areas.) As in the United States, the best visibility in Canada occurs in the mid-continental region, with a median for the prairie cities of about 13 dV. Urban centers of the west coast and of the maritime provinces of the east coast both have median visibility near 15 dV. Upper Canada, the region along the St. Lawrence River that includes Ottawa, Montreal and Quebec City, has a slightly hazier median level. Not surprisingly when compared with Figure 9.2, the Golden Triangle region of Canada, the populated region around the Great Lakes, shows the greatest light extinction with an average median near 20 dV. These urban values closely match the rural values shown south of the border in Figure 9.2.

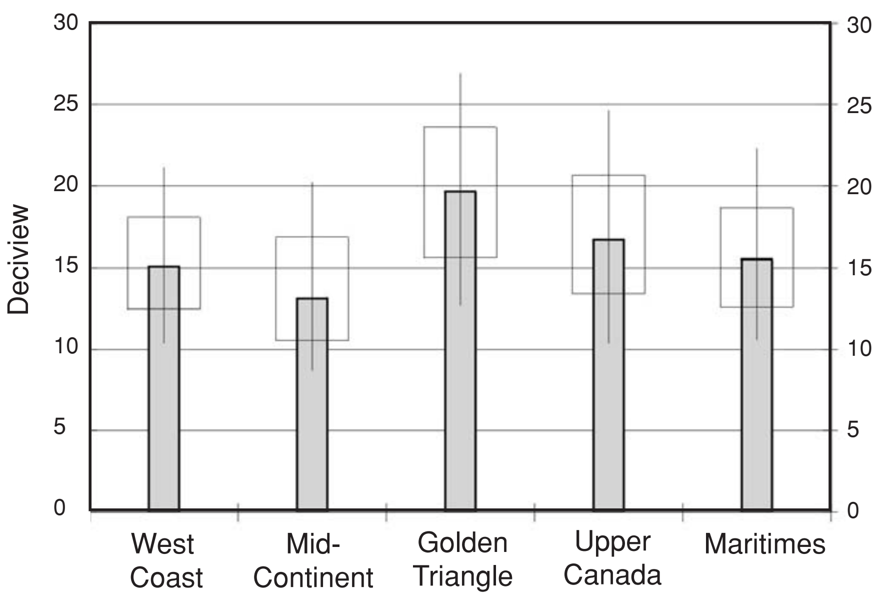


Figure 9.3. Light extinction statistics (west to east) in deciviews for Canadian urban regions, calculated from fine PM measurements. The height of the gray bar indicates the median. The 10th to 90th percentile range is described by the thin line and the 25th and 75th percentiles are defined by the box. (Based on McDonald, 2002).

Reported long-term visibility information for Mexico is limited to the Mexico City area. At two observation sites there, the mean visual range attributable to air pollution has been less than 10 km during the 1990s (Mora et al., 2001). In terms of the deciview index used in Figures 9.2 and 9.3, the corresponding extinction is greater than 37 dV. (As a comparison with another urban area, the light extinction in Washington, D.C., measured and calculated on the same basis as the information shown in Figure 9.2, is 24 dV.)

Visibility in much of the rural United States has generally improved in the past two decades, especially in the eastern half of the country. The widespread improvement in visibility reverses a trend of decreasing visibility during the preceding quarter century. This improvement is not uniform under all conditions, however. For example, although visibility generally has improved at most national parks and wilderness areas throughout the country between 1988 and 1998, the 20 percent of the days with the worst visibility are showing further degradation at some such locations (Sisler and Malm, 2000). The recent visibility improvement that has occurred is associated with a reduction in $PM_{2.5}$ concentrations throughout much of the country. It is largely attributable, in the eastern United States at least, to a decrease in $SO_4^{=}$-containing particle concentrations as a result of mandated reductions in SO_2 emissions from electric power plants in the mid 1990s.

Visibility-monitoring information in Canada is limited spatially and temporally, making an assessment of trends difficult. Airport visual-range observations have not been found useful for characterizing the whole range of visibility conditions in much of the country because visual ranges reported by the Meteorological Service of Canada often have a maximum of 15 miles (24 km).

Available data are not sufficient to evaluate visibility trends in most of Mexico. In Mexico City the visual range is reported to have decreased from 4 to 10 km in 1940 to 1 to 2 km in recent years, with 2 to 4 km of the decline occurring in the 1950s (Ciudad de México, 1999).

A full understanding of visibility throughout North America will require more extensive measurements in many areas. *Long-term monitoring of PM mass concentrations and composition, using consistent protocols, should be done throughout North America to assess spatial and temporal visibility trends.*

9.1.2 Factors Affecting the Relationship between PM and Visibility

The relationship between the light extinction coefficient and the PM mass concentration depends on the sizes and chemical compositions of the particles, and the ambient relative humidity. The roles of these factors and the relationships that result are discussed below.

Particle Size. The effectiveness of particles at scattering light depends on their sizes. Particles whose diameters are approximately the same as the wavelength of light are the most efficient, in terms of light scattering per unit mass (the scattering efficiency). As shown in Figure 9.4, particles whose diameters are between 0.3 and 1.0 µm tend to scatter the most light per unit mass. Since the human eye is most sensitive to light with wavelengths in the vicinity of 0.5 µm, these effects are very evident to human observers. Note that larger particles, such as those in the coarse mode with diameters between 2.5 and 10 µm, are not very efficient at scattering light.

Particles with diameters in the general vicinity of 0.5 µm also account for most of the mass in the fine-particle fraction ($PM_{2.5}$). As a result, the $PM_{2.5}$ mass-concentration corresponds to those particles that are most efficient at scattering light.

Chemical Composition. As has been described earlier in this report, the principal chemical constituents of particulate matter are $SO_4^{=}$, NO_3^{-}, BC, a broad variety of OC compounds, crustal (soil) compounds, water, and small amounts of some other species, such as potassium from vegetation burning, sea salt, and various trace metals. Figure 9.4 demonstrates that the scattering efficiency varies somewhat with chemical composition for a given particle size. Note that BC (labeled "Carbon-2" on the figure), does not scatter light as effectively as other species: it is very effective at absorbing light, however (which is not portrayed in Figure 9.4).

In actuality, the aerosol is not composed of particles of a single species, but rather is a mixture. It can be considered as externally mixed, in which each species is found in separate particles, or as internally mixed, in which several species are combined in a single particle. Actual ambient aerosol appears to be a combination of both types of mixtures. Particles formed at different times in different air masses may mix together to form an external mixture, while particles formed by secondary processes and condensation from a mixture of precursors may be internally mixed. This complex structure makes it difficult to calculate the light-extinction properties

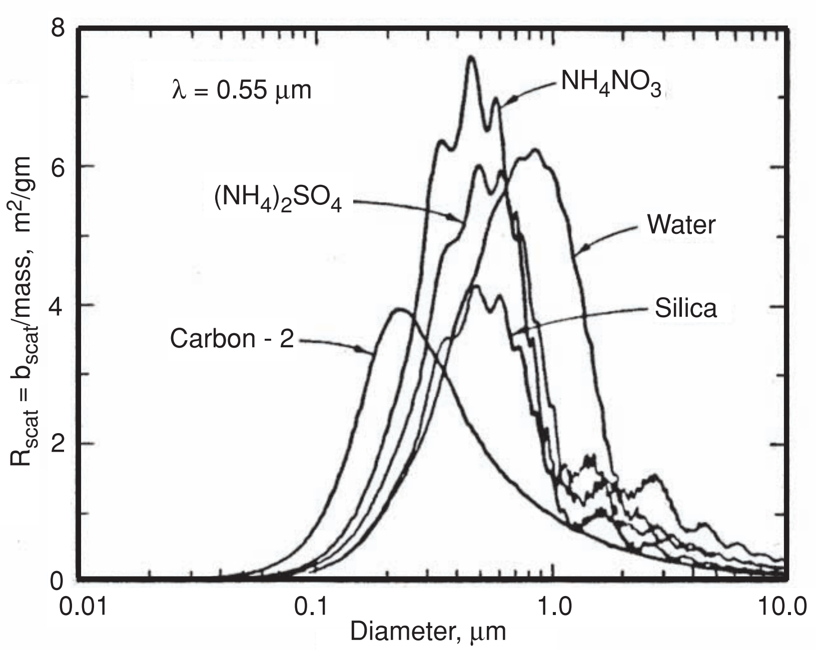


Figure 9.4. Calculated light scattering efficiency vs. particle diameter for several chemical species (Shah, 1981).

For example, Figure 9.5 illustrates the growth in light scattering with increasing relative humidity for pure NH_4NO_3, $(NH_4)_2SO_4$, and a mixture of the two, at two different particle sizes. The increase in scattering going from 40 percent relative humidity to 97 percent is nearly a factor of ten for the particles that are originally 0.3 μm in diameter. The relative increase in scattering for the 0.6 μm particles is a bit less because the initial scattering is already around the peak shown in Figure 9.4.

The influence of relative humidity on the growth of light scattering by particles that contain organic compounds is not as well quantified as it is for inorganic species. Furthermore, the physical location of the organic material in or on a particle may affect the particle's affinity for water. For example, some particles that originate in urban areas may have an organic film on their surfaces that inhibits the uptake of water by the hygroscopic salt inside. Thus, although a particle may be composed predominantly of a hygroscopic salt, the organic coating could reduce its effective hygroscopicity.

of individual real particles and, as discussed below, empirical estimates of extinction efficiencies are used instead.

As was described in Chapter 3, some of the material in ambient aerosol particles is semivolatile; that is, it can change phase from gas to particle, and back again, depending on ambient conditions such as temperature, relative humidity, and gas-phase concentration. The principal semivolatile species of interest for visibility are NH_4NO_3 (which is in equilibrium with gaseous HNO_3), the ammonium ion associated with some sulfates and nitrates (which is in equilibrium with NH_3 gas), and some organic compounds that are in equilibrium with volatile organic compounds (VOCs).

Humidity. An important factor that affects particle size, and hence the scattering efficiency of a species, is the water that is adsorbed by some hygroscopic species – sulfates, nitrates, and some organics. The amount of water uptake depends on the chemical species, the structure of the particle, and on the ambient relative humidity. At high relative humidity the size of a particle can be several times that of the dry particle, as was shown in Figure 3.4. This results in an even more dramatic effect on light extinction.

9.1.3 Empirical Relationships between PM and Visibility

Light extinction can be broken down into the sum of its scattering and absorption components as follows:

$$b_{ext} = b_{Ray} + b_{ag} + b_{sp} + b_{ap},$$

where

b_{ext} = light extinction coefficient

b_{Ray} = Rayleigh scattering (light scattering by molecules of air)

b_{ag} = light absorption due to gases (mainly NO_2)

b_{sp} = light scattering by particles

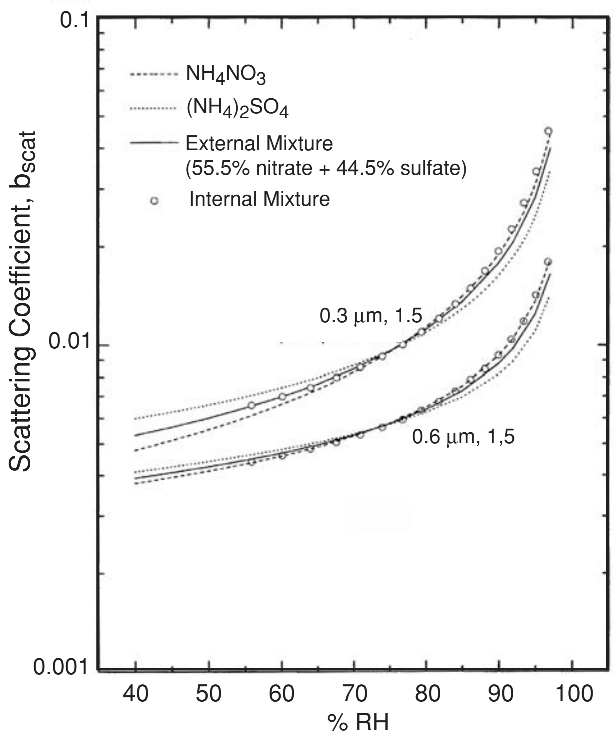


Figure 9.5. Effect of relative humidity on light scattering by mixtures of NH_4NO_3 and $(NH_4)_2SO_4$ (Tang, 1996). Reproduced by permission of the American Geophysical Union.

b_{ap} = light absorption by particles.

The scattering and absorption by gases (b_{Ray} and b_{ag}) can be calculated readily knowing the air pressure (altitude), temperature, and the concentration of NO_2. To deal with the particle-related extinction (b_{sp} and b_{ap}), one can allocate portions of the extinction to each species of the mixture and then sum the contributions to arrive at the total particle-caused extinction. This construction is sometimes called chemical extinction (Watson, 2002). Although there are complex theoretical considerations that limit the rigor of such an approach when assigning culpability to a particular species (White, 1986), the approach has been found useful for estimating the relative contributions of various species to the total light extinction.

The formulas typically used for chemical extinction are, for scattering of light by particles,

$$b_{sp} = e_{Sulfate}[Sulfate] + e_{Nitrate}[Nitrate] + e_{OMC}[OMC] + e_{FSoil}[FSoil] + e_{Other}[Other] + e_{Coarse}[Coarse]$$

and, for absorption of light by particles,

$$b_{ap} = e_{BC}[BC]$$

where

[Sulfate] is the concentration of fine sulfate-containing compounds

[Nitrate] is the concentration of fine nitrate-containing compounds

[OMC] is the concentration of fine organic carbon compounds

[FSoil] is the concentration of soil compounds in the fine fraction

[Other] is the concentration of other species in the fine fraction

[Coarse] is the concentration of all species in the coarse fraction

[BC] is the concentration of black carbon

e_X is the scattering efficiency (or, for BC, the absorption efficiency) of species X.

The scattering (or absorption) efficiency e_X is interpreted here as the scattering (or absorption) attributable to a unit concentration of species X. The value of e_{BC} sometimes also includes the contribution to scattering, which is small compared to the absorption. Here, fine particles are those that make up $PM_{2.5}$ and the coarse-particle concentration equals $[PM_{10}]$ - $[PM_{2.5}]$. Since the amount of material described as "Other" is typically very small, that term is often ignored.

Note that, in most cases, the concentrations used in the above formula are those of chemical compounds, not specific ions or elements. Since the full molecular form may not be measured, or even known, empirical factors are sometimes used to estimate the mass concentration of the compound based on ionic or elemental measurements. Examples include assuming $(NH_4)_2SO_4$ and NH_4NO_3 for $[SO_4^=]$ and $[NO_3^-]$, specific oxides for the soil compounds, and an empirical (and poorly quantified) factor to scale up the OC concentration to represent the contributions of hydrogen, oxygen, and other elements to [OMC]. (See Section 3.5.3 for a discussion of the carbon factor.)

The three equations above describe a light-extinction budget (LEB). This is the approach that was used to derive the light extinction values in Figures 9.2 and 9.3 from measured particle species concentrations.

Values for all the e_X have been developed by a variety of theoretical and experimental means. Extinction efficiencies are not fundamental constants, but rather vary with the size distribution, the properties of the particles, and the molecular composition of the sulfates, nitrates, and OC. Thus it is only a crude approximation to use a single value of e_X to represent the extinction efficiency at different locations or at different times. Also, as discussed, the e_X for $SO_4^=$, NO_3^-, and OC depend on the relative humidity. Various empirical formulas have been developed for sulfates and nitrates to represent the type of humidity-dependent behavior that was illustrated in Figure 9.4. There is little agreement on how to represent the humidity-dependent behavior of e_X for OC, however, although half the $SO_4^=$ or NO_3^- growth factor has been used as a compromise in some work (e.g., Malm et al., 1994). The current approach used by the U.S. IMPROVE network, which provided the information in Figure 9.2, is to assume that organics do not reflect any humidity-related growth. *Research is needed to develop a better understanding of the hygroscopicity of organic components of particulate matter.*

To illustrate the relative magnitudes of the various e_X, the predominant ranges of values of e_X deduced from various studies are presented below. The units are Mm^{-1} per $\mu g/m^3$, hence m^2/g. All values are for dry particles; recall that the contribution of water can multiply the given $SO_4^=$ and NO_3^- efficiencies many fold at high relative humidities, while the effect of water on the OC efficiency at any specific location is an open question. The ranges of prevailing dry extinction efficiencies listed below indicate the uncertainty that could result from using fixed extinction efficiencies (such as those used by IMPROVE, listed in parentheses) under varying circumstances.

$$e_{Sulfate} = 1.5 \text{ to } 4 \text{ m}^2/\text{g } (3 \text{ m}^2/\text{g})$$

$$e_{Nitrate} = 2.5 \text{ to } 3 \text{ m}^2/\text{g } (3 \text{ m}^2/\text{g})$$

$$e_{OMC} = 1.8 \text{ to } 4.7 \text{ m}^2/\text{g } (4 \text{ m}^2/\text{g})$$

$$e_{Fsoil} = 1 \text{ to } 1.25 \text{ m}^2/\text{g } (1 \text{ m}^2/\text{g})$$

$$e_{Coarse} = 0.3 \text{ to } 0.6 \text{ m}^2/\text{g } (0.6 \text{ m}^2/\text{g})$$

$$e_{BC} = 8 \text{ to } 12 \text{ m}^2/\text{g } (10 \text{ m}^2/\text{g}).$$

From the perspective of air-quality management, the above values show that the biggest visibility benefits per unit change in concentration are gained by reducing sulfates, nitrates, organics, and BC, because they have the largest efficiencies. In humid areas the visibility benefit of reducing sulfates, nitrates, and (perhaps) organics is even greater because of the effect of adsorbed moisture. On the other hand, it would take about five to fifteen times as great a reduction in coarse-particle mass concentration to equal the benefit of reducing the concentration of one of the four most efficient species by a given amount.

Based on three recent years of PM measurements made by the IMPROVE program (Malm, 2000b) and light-extinction calculations made using the formulas above, Figure 9.6 presents the proportion of rural particle extinction that is contributed by the individual chemical constituents (including associated water) in several regions of the United States. The positions of the pie diagrams are in a roughly geographic arrangement. The relative contributions of the various species in these diagrams illustrate implications for control options as a consequence of the combination of the relative magnitudes of the extinction efficiencies described above and the regional composition of ambient PM described in Chapter 6. (Figure 9.6 can be compared with a similar presentation for speciated mass concentrations in Figure 6.12.)

According to this figure, $SO_4^=$-containing particles and associated water dominate rural light extinction throughout much of the country, particularly in the eastern half, which implies that sulfur controls are a necessary part of most programs to improve regional visibility. The exception is southern California, where the proportion of extinction due to NO_3^--containing particles is greatly enhanced by NO_x emissions from nearby urban areas. (A similar enhancement of the NO_3^- contribution is observed at the IMPROVE sampling site in Washington, D.C., which is not shown here.) Organic-containing particles produce a greater fraction of the extinction in the West than in the East, offering another means for visibility improvement. Black carbon is a fairly consistent, but small, relative contributor across the continent, while the relative contributions due to fine soil and coarse particulate matter can be substantial in the more arid regions.

Although it is not shown in Figure 9.6, the composition for Denali National Park in Alaska looks very much like the one for the Colorado Plateau. The total extinction there, as represented by the sum of the species contributions, is a somewhat clearer 20 Mm^{-1}.

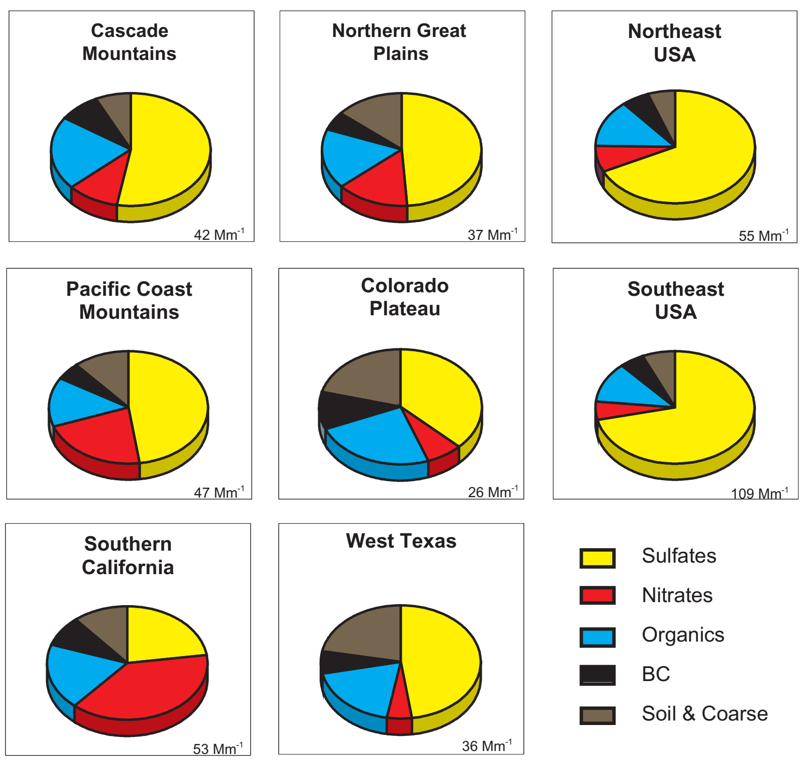


Figure 9.6. Relative contributions of PM constituents (including associated water) to particle-caused light extinction for several rural regions of the United States, calculated from IMPROVE PM measurements from March 1996 through February 1999. The numerals are the total chemical extinction (the sum of the component contributions) at each region. (Derived from data in Malm, 2000b).

9.1.4 What are Some Special Issues with Visibility?

The above technical discussion has shown that the linkage between visibility and particulate matter is a complex one. To set the stage for later discussion on visibility management, it is useful to lay out some special factors that have to be considered. They include the following:

- Under conditions that prevail in the atmosphere, some species (fine crustal particles and coarse particles of all compositions) are much less efficient, per unit mass, at scattering or absorbing light than are other species ($SO_4^=$, NO_3^-, OC, BC). This means that reductions in the concentrations of some species will be more effective at improving visibility than will reductions in others. Since the more-efficient species are mostly in the form of secondary particles, in many cases air-quality management strategies that are regional and may encompass many states or provinces are likely to be more important for regional haze than are local strategies.

- In humid areas, the light-scattering efficiency of $SO_4^=$, NO_3^-, and (perhaps) some organics is greatly enhanced. This puts even greater emphasis on control of these species for effective mitigation of visibility impairment.

- Visibility tends to vary seasonally by an even greater extent than PM concentrations, because the effect of particle growth under high humidity is superimposed on the factors of temperature, availability of oxidants, and presence of clouds that affect the formation of secondary PM.

- In the clearest, almost particle-free air, only a minute additional amount of fine PM (1 µg/m^3) can reduce visibility by 20 to 30 percent. Therefore, strategies to preserve visibility on the clearest days may require stringent limitations on emission growth, and dilute impacts from very distant sources can still be important.

- At the other extreme, in locations such as urban areas, where the concentrations of PM are higher and visibility is more limited, visibility is relatively insensitive to small changes in PM concentrations. Rather, substantial decreases in PM concentrations (typically greater than 20 percent) are required to achieve perceptible changes in visibility.

- Visibility is perceived instantaneously, so there is no averaging over time, as is appropriate when considering the health effects of PM. As a result, visibility-management strategies may need to consider mitigation of brief episodes, such as might be caused by passage of plumes, as well as the longer-term effects of regional hazes.

- The level of the natural background is important for those situations where, for example, the goal is to minimize the anthropogenic influences on scenic visibility. Determining that background, which varies daily and consists of a mix of particles of soil dust, products of emissions from vegetation and oceanic spray, and emissions from wildfires, is difficult since it is not feasible to separate out man's influence. In addition to the natural background, emissions from human activities throughout the globe and in neighboring countries also affect the overall visibility, but are beyond the reach of a single nation's visibility-management program.

- The actual appearance of a view depends not only on the extinction coefficient, but also on the color and contrast of the scene, the sun angle relative to the sight path (which changes during the day), and the presence of clouds in the sky. These factors mean that the human perception of different scenes, or of the same scene at different times, may differ even though the extinction coefficient and the PM concentration and composition are unchanged.

9.2 ROLES AND USES OF PM AND OPTICAL MEASUREMENTS IN VISIBILITY ASSESSMENT AND MANAGEMENT

Measurements and modeling are the two basic approaches for assessing visibility conditions and for developing strategies for managing visibility. Measurements serve to describe current situations and provide data for developing, testing, and applying air-quality models for visibility. Modeling, which is discussed in the next section, is used to forecast future situations and to estimate the effects of visibility management strategies. Modeling also can be used to fill in estimates of current data between measurement locations and times.

Measurements of pollutant-species concentrations, atmospheric optical parameters, meteorological conditions, and the appearances of scenes or objects all play roles in describing visibility conditions and the contributions of air pollution to those conditions. Methods for making many of these measurements have been discussed in Chapter 5. Their roles in characterizing visibility and the contributions of air pollutants are discussed here.

9.2.1 Long-Term Monitoring Programs

The earliest routine measurements of visibility were those of prevailing visibility by human observers at airports. A data base of more than five decades is now available for the United States, and has been used to determine the spatial distribution and trends of visibility (see, for example, Chapter 6 of this report). Current airport visibility data even have been used to characterize visibility over the entire globe (Husar et al., 2000). Automatic observations of airport visibility by the Automated Surface Observing System (ASOS) and the Automated Weather Observation System (AWOS) (see descriptions in Chapter 5) are replacing human observers in many locations, which will eventually bring an end to the human-observer data base in most jurisdictions

Since the focus of airport observations is for the safety of aircraft operations, there is sometimes an artificial maximum to the reported visibility. For example, the maximum prevailing visibility often reported at Canadian airports is 15 miles (24 km) and the new ASOS and AWOS light-scattering data at airports in the United States are routinely reported to a maximum visual range equivalent of 10 miles (16 km). These upper bounds in reported data limit the usefulness of these methods in areas with good visibility. However, some ASOS optical data are being archived at full instrument resolution. *ASOS and AWOS light extinction measurements from all locations, archived with a time resolution of one-hour average or shorter, should be made readily available for purposes of tracking air-pollution-related visibility.*

Regional long-term monitoring of aerosol and visibility began in the national parks and wilderness areas of the western United States in 1978-79 under the Western Fine Particle Network (WFPN) and the National Park Service's visibility monitoring network (Flocchini et al., 1981; Malm and Molenar, 1984). Information from these two networks provided a mapping of rural visibility and PM in the West.

The WFPN measurements, which did not include carbon, led initially to the conclusion that $SO_4^=$ played the dominant role in western U.S. visibility (Malm and Johnson, 1984). However, subsequent measurements of the PM carbon fraction, such as in the Western Regional Air Quality Studies (WRAQS; Tombach et al., 1987), indicated that these initial conclusions had overstated the relative contribution of $SO_4^=$ to extinction in the West (White, 1985; White and Macias, 1989).

Five years (1984-89) of detailed measurements were made in the U.S. Southwest, in the general vicinity of the Grand Canyon, by SCENES (Subregional Cooperative Electric Utility, Department of Defense, National Park Service, and Environmental Protection Agency Study; Mueller et al., 1986). In addition to providing much insight into the composition of the aerosol, SCENES also produced advances in optical and aerosol measurement technology, including improved means of quantifying atmospheric concentrations of semivolatile species (especially nitrates and organics).

A comprehensive characterization of Class-I area visibility and aerosol throughout the entire United States began with IMPROVE (Interagency Monitoring of Protected Visual Environments), which initiated operation in 1988 (Malm et al., 1994). Many of the advances in measurement technology developed by WRAQS and SCENES were incorporated into IMPROVE, which replaced the WFPN. IMPROVE was substantially expanded in 2000 (Pitchford et al., 2000) for the purpose of providing 5 years of baseline measurements for the U.S. national regional haze management program. One of the results of the IMPROVE measurements is a sufficiently long data base to infer trends, such as those that were discussed earlier in this chapter.

Because PM in the U.S. Southeast is different from that in the West, a multi-year program of measurements was initiated in the Southeast in 1998. The study, named SEARCH (Southeastern Aerosol Research and Characterization; Hansen et al., 2000; Jansen et al., 2001), is planned to run through 2005. SEARCH now includes optical measurements, coupled with in-depth, state of the art, particulate and gas-phase measurements, at eight urban and rural locations. For the purposes of understanding visibility in this section of the country, these measurements will supplement those of IMPROVE and will provide insight on the relationships between urban and rural conditions.

The U.S. EPA has recently initiated speciated fine-particle measurements, similar to those of IMPROVE, in both urban and rural areas throughout the country. These measurements will be useful for estimating visibility outside of the scenic areas that are the focus of IMPROVE. Some methodological differences mandate care when comparing measurements made by the two programs, however.

Measurements of PM and light extinction have also been made at a few locations in Canada, near the border with the United States (Hoff et al., 1997), under a program called GAViM (Guelph Aerosol and Visibility Monitoring). The PM measurements use part of the IMPROVE sampling system, and thus can be compared with U.S. measurements.

Such long-term measurement programs have provided insight into the causes of visibility impairment, its temporal and spatial variability, and its year-to-year trends over much of North America. Several of the studies have included, or currently include, research components that address specific issues concerning the physics and chemistry of the aerosol or of atmospheric optics. These research efforts have provided considerable insight concerning the challenging visibility-related issues of particle-size distributions, semivolatile species, hygroscopicity of particles, and estimation of particle light-extinction efficiencies. Until very recently, however, the visibility studies have focused almost entirely on rural areas, especially national parks and wilderness areas. Insight at the same level of detail is not yet available for urban visibility, except from a few of the short-term studies that are described below.

9.2.2 Short-Term Measurement Programs

A multitude of shorter-term studies (typically involving a year or less of measurements) has focused on specific visibility issues in the United States. Many of them have been concerned with determining the effects of specific emission sources or source regions on visual air quality, and thus demonstrate the application of measurement and modeling approaches to visibility management. There are too many studies of this type to describe them all here, but significant recent ones are summarized in Table 9.1.

Electric power-plant emissions were a major focus of interest of almost all of the short-term studies in Table 9.1. In fact, the last three studies in the table were followed by actions to reduce emissions from the targeted sources, and results of the research studies played a role in leading to these actions. One factor contributing to this emphasis may be that the point-source emissions from electric power plants are easier to identify than the dispersed emissions from the area sources that characterize urban areas and are the other major sources of visibility-impairing PM.

In addition to the studies noted in Table 9.1, major visibility-related urban studies have been carried out in Tucson, Arizona, in 1994; Phoenix, Arizona, in 1990; and Denver, in 1982 and 1987. The 1987 South Coast Air Quality Study (SCAQS) in the Los Angeles basin also had a visibility component.

Short-term studies focused on urban areas and their surroundings have also taken place in Canada and Mexico. In Canada, the area in the vicinity of Vancouver, on the Pacific Coast, has been the subject of several air-quality studies that have included a visibility component. The most recent such study took place in September 2001. In Mexico City, a short-term study in 1997 measured both the chemical composition of $PM_{2.5}$ (Chow et al., 2002) and light scattering and absorption (Eidels-Dubovoi, 2002).

9.2.3 An Example of a Scenic Visibility Setting – The Colorado Plateau

As an example of the understanding provided by studies such as those described above, a description of the aerosol and visibility situation in the Colorado Plateau area of the western United States is provided here. The Colorado Plateau, which lies west of the Rocky Mountains, contains Grand Canyon National Park and several other well-known scenic areas for which good visibility is considered a national asset. The description provided here for visibility can be compared with those for PM presented in Chapter 10. Much of the aerosol and visibility information presented here is found in Malm (2000b).

The average visibility on the Colorado Plateau, in terms of light extinction, is about 9 deciviews (25.6 Mm^{-1}), as was indicated in Figure 9.2. This corresponds to an average visual range of about 150 km. Although conditions vary over the wide geographic extent of the Colorado Plateau, the annual average is relatively uniform over the region. The 20 percent of the days with best visibility average in the range from 4 to 6 dV (about 15 to 19 Mm^{-1}), while the 20 percent of the days with the poorest visibility average in the range from 11 to 15 dV (30 to 45 Mm^{-1}).

The average $PM_{2.5}$ concentration in this region is 3.0 $\mu g/m^3$, a value that is well below the U.S. national annual $PM_{2.5}$ standard of 15 $\mu g/m^3$. The average concentration of coarse mass (PM_{10} – $PM_{2.5}$) is 4.3 $\mu g/m^3$. The principal components of $PM_{2.5}$ are $SO_4^{=}$ (35 percent) and OC (32 percent), with fine soil contributing 22 percent. Nitrates and BC each account for around 6 percent. The composition of the coarse

Table 9.1. Recent short-term visibility measurement programs.

Study Name, Year Of Observations, And Location	Description And Comments	References
CRPAQS (California Regional $PM_{10}/PM_{2/5}$ Air Quality Study), 1999-2000. Central California.	Regional characterization and modeling of PM and visibility, and the emission sources that contribute to them. Data analysis is ongoing.	Magliano and McDade (2001)
BRAVO Study (Big Bend Regional Aerosol and Visibility Observational Study), 1999. Texas.	Characterization of aerosol and visibility in the vicinity of Big Bend National Park, tracer study of atmospheric transport, and modeling of contributions of source regions in Texas and Mexico. Conclusions available in 2003.	Green et al. (2000)
Big Bend National Park Regional Visibility Preliminary Study, 1996. Texas and Mexico.	Bi-national cooperative measurement program in both Texas and Mexico in 1996. Precursor to BRAVO.	Big Bend Air Quality Work Group (1999); Gebhart et al. (2000)
SEAVS (Southeastern Aerosol and Visibility Study), 1995. Great Smoky Mountains National Park.	Research to characterize the chemical and optical properties of the aerosol in the Southeast. Concluded that more reliable techniques are needed for measuring OC in particulate matter.	Andrews et al. (2000)
Dallas-Ft. Worth Winter Haze Project, 1994-95. Northeastern Texas.	Study of wintertime visibility and aerosol in the Dallas-Ft. Worth area and assessment of the contributions of distant coal-burning power plants to the haze there. Concluded that the plant emissions contributed “subtly” to the haze	Tombach et al. (1996); McDade et al. (2000)
Mt. Zirkel Visibility Study, 1995. Yampa Valley, Colorado.	Study of the causes of visibility impairment at the Mt. Zirkel Wilderness Area with elevations above 3000m. Emphasis on the contributions of two coal-fired power plants some 50 km distant. Concluded, based largely on a videotaped observation, that the two power plants contributed at times to puffs of haze in the wilderness area, but that the haze was generally of more regional origin.	Watson et al. (1996)
Project MOHAVE (Measurement of Haze and Visual Effects), 1992. Southern Nevada and northern Arizona, including Grand Canyon National Park.	Field and modeling study of the effect of emissions from the coal-fired Mohave Generating Station and other sources on visibility in Grand Canyon National Park. Concluded that the generating station was generally an insignificant contributor to visibility impairment at the Grand Canyon, which is mostly attributable to other sources, but that the plant’s contribution could occasionally be important.	Pitchford et al. (1999)

fraction has not been studied routinely, but is presumed to consist mainly of soil.

The contributions of these species to light extinction have been displayed in Figure 9.6. At the Colorado Plateau, $SO_4^=$ accounts for 37 percent of the annual extinction due to particles (i.e., excluding Rayleigh scattering), followed by OC at 24 percent. These fractions differ from those for mass because of the enhancement of $SO_4^=$-particle scattering by moisture. The combination of fine soil and coarse particles accounts for another 21 percent. Black carbon accounts for 11 percent and NO_3^- for 7 percent.

The clearest days in the region tend to occur when there is transport from the northwest. Those air masses traverse a region of low emissions, and the concentrations of pollutants are further reduced by the aggressive atmospheric mixing that is typically associated with air masses arriving from that direction. The more typical transport is from the southwest. Since that transport route passes over the urbanized areas of southern Nevada, southern California and northern Mexico, transport from the southwest can be associated with poor visibility whenever the atmospheric mixing is limited. Poor visibility conditions can also occur on the Colorado Plateau during the monsoons of late summer, when transport from the south, passing over urban areas, smelters and power plants in Arizona, New Mexico, and Mexico, is combined with high relative humidity.

In addition to the contributions due to transport of pollution from distant urban areas, sources of air pollution in and near the Colorado Plateau include emissions from several coal-fired power plants, and local generation of fugitive dust from disturbed soil and motor-vehicle travel in this arid region. Also, prescribed and wild vegetation fires cause substantial episodic air-pollution and haze events.

The power plants can produce plumes that are visibly brownish-yellow due to light absorption by NO_2, but their impact on regional visibility is due to the formation of $SO_4^=$ from SO_2. Although the rate of formation of $SO_4^=$ is slow in the clear skies that are typical of this region, several studies have indicated rapid formation of $SO_4^=$ and haze when the emissions interact with moisture in clouds. The major coal-fired power plants in the region have installed SO_2 control systems in recent years, or are scheduled to do so in the next few years, so one should expect decreases in the $SO_4^=$ contribution to visibility from the amounts that were described above.

As part of the U.S. regional-haze program, the Western Regional Air Partnership (WRAP) has developed a strategy to continue to reduce power-plant emissions and is currently developing strategies to mitigate emissions of fugitive dust and fires that affect the Colorado Plateau. Additional progress in protecting visibility will have to come from emission-control efforts in urban areas in the United States and Mexico.

9.2.4 Can One Use PM Studies for Visibility?

All of the studies described in this section have one common feature – they were specifically designed, at least in part, for the purpose of addressing visibility impairment. Since PM measurements for the purpose of complying with health-based standards or for research on the health effects of PM are more common than those for visibility, the question arises as to whether one can use the information from a PM measurement program for visibility purposes. The answer is a qualified "Yes" - provided that the measurements include the concentrations of the optically-important species in $PM_{2.5}$ and care has been taken to minimize sampling artifacts for semivolatile species. Measurements of the mass concentrations of $PM_{2.5}$ and PM_{10} without speciation, which are the primary measurements of most routine PM monitoring programs, are not of great use for visibility characterization.

If the species concentrations are available, they can be used to estimate the allocation of light-extinction to each species, following the light extinction budget method described in Section 9.1.3. Measurements of the relative humidity and of the coarse-fraction mass concentration are also needed to carry out this process. (These data are also useful for the air-quality modeling that is described in the next subsection.) More rigorous calculations of light-extinction contributions require measurements of the particle-size distributions in the fine fraction, however, which usually are not available in most PM studies.

9.3 HOW ARE MODELS USED IN VISIBILITY MANAGEMENT?

Visibility models produce estimates of the optical effects of simulated or measured distributions of PM and gases. The typical output is the spatial distribution of the light-extinction coefficient or a description of the color and opacity of a plume. Some visibility models also include modules that emulate aspects of the response of the human eye-brain system to these optical effects, and thus describe the effects of the PM on the appearance of an actual scene.

Visibility models are used for much the same purposes as other air-quality models. One application is to simulate present and past conditions where optical or visibility measurements were not made or are not feasible, usually for the purpose of better understanding the factors that affect current visibility. Such modeling can also fill in spatial and temporal gaps in measurements. A second application is to simulate future conditions and thus to project future trends in visibility, usually for the purpose of developing and evaluating air-quality management strategies. Another related purpose is the assessment of impacts of a proposed new source or benefits of applying emission controls to existing sources.

9.3.1 What Specific Features are Required when Modeling Visibility?

Visibility modeling commonly starts with application of a chemical transport model (CTM), such as described in Chapter 8. (The exception is when the optical or visual effects of a measured actual aerosol are to be calculated.) A plume model is the starting point for analyzing a plume-blight situation, while a three-dimensional CTM would be used for regional haze. The minimum outputs needed from the CTM are spatial distributions of PM species concentrations (both fine and coarse), NO_2 gas concentrations, and relative humidity. The chemical species of interest for visibility are described in Section 9.1.

The simplest visibility models use the species' concentrations, together with assumed scattering and absorption efficiencies, to arrive at local descriptions of extinction through the empirical formulas given in Section 9.1.3. More advanced models calculate particle scattering based on the physics of the interaction of light with particles. Such aerosol-optics models also require information concerning the particle-size distribution of the aerosol, which generally has to be estimated based on specialized measurements. Since not all of the above information is produced routinely by CTMs, the intended use of the CTM outputs for visibility modeling must be taken into account when setting up the modeling exercise. One should note that models developed for PM_{10} alone or those that deal only with primary PM do not provide an adequate foundation for visibility modeling.

Visibility is of concern at all time scales, from instantaneous observations to averages over periods of years. Because visibility management tends to depend on measurements of PM, and these are typically made over 24 hours in routine networks, modeling with hourly resolution (and averaging over 24 hours) is generally the shortest time frame required. At the other extreme, there is a need to characterize conditions over longer periods, such as the annual averages used in some Canadian analyses and those 20 percent of the days in a 5-year period that reflect the worst visibility that are used in the U.S. regional haze program. For practical reasons, simulations over such long periods of time typically involve compromises – either a simplified model with coarse spatial resolution and/or simplified chemistry has to be used, or the longer period is constructed as a combination of a limited number of shorter periods that reflect the range of atmospheric or emission conditions of interest.

Ideally, light extinction is calculated directly through mechanistic models that consider the effects of individual particles on the transmission of light. Such calculations are sensitive to the size distribution of the particles. Chapter 8 notes that the ability of models to construct size distributions of secondary particles or to use detailed size-distribution information explicitly in the simulation is currently embryonic, and that few successful CTM simulations have been reported with size-resolved and/or chemically resolved PM anywhere in North America. Therefore, the capability of using a CTM and then specifically modeling the light extinction caused by the predicted PM is currently quite limited.

However, as was noted in Section 9.1.3, light extinction can be estimated from speciated chemical concentrations and assumed extinction efficiencies. This simplified approach eliminates the need for detailed information about the particle-size distribution, and thus places fewer demands on the CTM. Such an estimating technique for determining light extinction is used in several air-quality models, as described below, and is the basis for determining light extinction from both modeled and measured PM concentrations under the U.S. EPA's Regional Haze Rule.

9.3.2 Are Current Models Able to Simulate Visibility Conditions?

Different modeling approaches are used for simulating the visibility effects of point sources and of multiple sources over a region.

For point sources, modeling the appearance of a coherent plume and its effect on visibility (typically within 50 km of the source) requires a different method than the modeling of the visibility impact of a more dispersed plume at greater distances. For regulatory applications, the U.S. EPA has established detailed procedures for modeling the dispersion and optical effects of a plume and the PLUVUE-2 model is recommended for treating the effects of a coherent plume on contrast and color.

For greater distances from the source, the U.S. Interagency Workgroup on Air Quality Modeling (IWAQM) has recommended that, for regulatory purposes, the CALPUFF model be used to simulate long-range transport from point sources. CALPUFF simulates the dispersion of emissions from point sources and includes simple representations of the formation of $SO_4^=$ and NO_3^- from SO_2 and NO_x. CALPUFF is being proposed by the U.S. EPA as a preferred model for simulating long-range (>50 km) PM impacts from point sources. Furthermore, CALPUFF is the recommended tool for managers of national parks and wilderness areas to use for assessing the long-range visibility impacts of proposed point sources (FLAG, 2000). Using CALPUFF for modeling the combined effects of many sources of different types becomes cumbersome, however, and its chemistry calculations are too simplistic to deal with interactions between emissions from different sources.

Other plume-aerosol and visibility models, applicable over a wide range of travel distances and with more advanced simulation of the diffusion and chemical processes than either PLUVUE-2 or CALPUFF, are also available. Examples include the Reactive and Optics Model of Emissions (ROME; Seigneur et al., 1997) and the second-order closure puff model SCICHEM (Karamchandani et al., 1999).

Simulating regional distributions of visibility requires a three-dimensional CTM. The set-up and input needs for determining PM concentrations with this kind of model are significant, as described in Section 8.2. The additional calculation of light extinction can increase this complexity substantially if detailed aerosol optical calculations are made, or it can require relatively little additional resources if empirical light-extinction efficiencies of the species are used. For visibility, as with the PM calculations, calculation of the inorganic PM contribution is significantly more straightforward and certain than the calculation of the secondary organic contribution.

A regional air-quality model system that has been developed with visibility applications in mind is the Community Multiscale Air Quality (CMAQ) Modeling System developed by the U.S. EPA. CMAQ can explicitly calculate light extinction from particle properties (Mie theory approach) or via the simplified approximate approach of using species concentrations and extinction efficiencies. CMAQ has been evaluated against measured visibility data for a summer season in eastern North America (Binkowski et al., 2001) and recent evaluations have been made by WRAP for the western United States and in BRAVO for the Texas area. These evaluations have shown that, at least with current versions of the model, the predictions of extinction tend to be less than the observations, though spatially- and temporally-averaged spatial patterns and increments of change are sometimes comparable to observations. Most other regional PM models (e.g., AURAMS, PM-CAMx, and the urban-scale model UAMV-PM) do not incorporate a module for the explicit calculation of light extinction, although some others (e.g., REMSAD) estimate extinction using the products of species concentrations and extinction efficiencies.

In addition to the physical and chemical modeling of source emissions, receptor-modeling and statistical techniques (such as factor-analysis methods) have been used to relate observed PM concentrations to source categories or regions of emissions, as described in Chapter 7. These methods can be extended to visibility. Such methods allow for easy identification of spurious events such as dust storms and forest fires. For the secondary PM that is important for visibility, however, assumptions may need to be made about conversion rates in order to apply such methods. If information is also available on meteorological trajectories, then the results of these techniques can be refined to give stronger estimates of the source apportionment for secondary PM and, hence, visibility.

A special form of visibility modeling uses the aerosol and optical information from a CTM or from measurements, calculates the effect of the aerosol on the contrasts and colors in an actual scene, and displays the results in a computer-modified photograph (Molenar et al., 1994). Such computer-generated images approximate how the scene will appear to the human eye, and thus provide a concrete visualization of the abstract concept of light extinction. Although the analyses and calculations involved for simulating one view are quite extensive, results can be demonstrated using simplified software that is available for use on a personal computer (WinHaze, 2002). Using slightly simplified algorithms, this software has been applied to demonstrate the effects of varying extinction levels on a number of views at several national parks and wilderness areas in the United States and in some other locations.

The simulation of the human perception of actual scenes by using photographs of computer images is not perfect, however. Based on color-matching experiments, Henry (1999) points out that such images are less colorful and bluer than the true scene, and therefore the artificial images overstate the visual effects of increasing haziness. Nevertheless, such images are useful for portraying the essential visual effects of extinction and the relationship to PM concentration, albeit only semi-quantitatively.

9.3.3 What Would Improve the Capacity to Model Visibility?

Models developed and tested for the purposes of estimating primary and secondary $PM_{2.5}$ concentrations are suitable for application to the visibility question, provided that there is also a means for calculating the optical effects of the PM, either within the model or in an external post-processor. Since visibility itself is an instantaneous response to atmospheric conditions, the basis for the model calculations should be short period (e.g., hourly) results, which then can be averaged for longer periods. Also, since current visibility regulatory programs are based on averages over many days (e.g., in the United States, over the haziest 20 percent of the days in a 5-year period) and the days of importance may be different for different locations in the modeling domain, the model's computing time needs to be taken into consideration.

Dealing with the critical uncertainties in CTMs for PM, which are described in Section 8.10, is equally relevant for modeling visibility. Particularly important concerns are descriptions of the meteorological field and shortcomings in emission inventories. In addition, there are some unique aspects to the needs for visibility modeling.

As one example, improvement in modeling of secondary organic PM will be important to visibility, both in urban areas and in those pristine areas that may have significant emissions of natural VOCs. One specific concern for regional visibility modeling in scenic areas is the validity of the gas-particle partitioning simulations, when applied in a clean environment rather than the polluted urban one for which they have typically been developed. Models that rely on condensibility through absorption will have difficulties due to the low PM concentrations found in pristine environments and also may not properly address increases in organic-particle growth with changes in humidity. Because of the necessary treatment of water chemistry, models whose approach addresses the water solubility of VOCs are most appropriate for visibility. Current models with sound treatment of water chemistry and ability to model condensational growth include, for example, GATOR, CMAQ and AURAMS.

Also, conditions on the 20 percent of the days with best visibility play an important role in the implementation of the U.S. regional-haze program. Many of those days have conditions very close to natural background. Natural background is problematic for modeling, because it derives partly from transport from outside the modeling domain and partly from geogenic and biogenic emissions within the domain. Furthermore, PM models are not optimized to simulate clean days. Rather, in order to predict or evaluate urban PM episodes, PM models are designed to simulate those days with the worst conditions. Testing remains to be done to determine how well those models perform when concentrations are representative of natural background or the days with best visibility.

9.4 ATMOSPHERIC PARTICLES AFFECT THE GLOBAL RADIATION BALANCE

Particles in the atmosphere influence the balance between the solar radiation that reaches the earth's surface and the infrared radiation that is transmitted back into space. This process occurs both directly (direct forcing), as the particles scatter and absorb incoming solar and outgoing infrared radiation, and indirectly (indirect forcing), as the particles influence cloud formation and precipitation, which in turn affect the radiation balance. Changes in the radiation balance due to changes in the amount and type of PM, natural or anthropogenic, are believed to contribute to climate change through a net cooling of the atmosphere. This process is described in detail in a report of the Intergovernmental Panel on Climate Change (IPCC, 2002).

During the past decade, significant steps forward have been made by the climate-change scientific community in elucidating the role of aerosols in the global climate balance. The second assessment report of the IPCC (1996) documented a high level of uncertainty associated with attributing radiative forcing to natural and anthropogenic aerosols. The main causes were a lack of knowledge of the vertical and horizontal spatial distributions of the particles in the atmosphere, the particle-size distributions, their chemical composition, and the arrangement of components within individual particles.

The IPCC's Third Assessment Report (IPCC, 2002) indicates that progress has been made in addressing these issues. Although much uncertainty remains concerning the contributions of atmospheric aerosols, progress has occurred with emission inventories, scaling-up of measured data, and development of global scenario modeling capacity. Field studies, network monitoring, and satellite analyses have provided both process-level understanding and a descriptive understanding of the aerosols in different regions. Three-dimensional global-scale aerosol models have been developed for carbonaceous particles from biomass and fossil fuel burning, as well as for dust, sea salt and NO_3^- and NH_4^+ in secondary particles. Indirect forcing remains subject to much larger uncertainties than direct forcing, which reflects uncertainties in the understanding of the effects of particles on the size distribution and number of droplets within a cloud.

Perturbations to the energy balance of the planet are usually expressed as radiative forcing in units of Watts per square meter (W/m^2), with positive values representing warming. Figure 9.7 summarizes the current understanding and level of uncertainty attached to the influences of greenhouse gases and atmospheric particles over the last 250 years. Carbon dioxide and the other well-mixed greenhouse gases represent the greatest forcing at +2.4 W/m^2 with a high level of scientific understanding. Net increases in PM concentrations are estimated to counter this forcing (i.e., they contribute to cooling) by anywhere from a negligible amount to more than about –2.5 W/m^2. As this large range suggests, the uncertainties relating to aerosol radiative forcings remain very large, mainly because the values rely to a great extent on estimates from global modeling studies that are difficult to verify.

Figure 9.7 presents a first-order perspective on a global, annual-mean scale. In actuality, all the forcings have distinct spatial and seasonal features. For example, Figure 9.8 illustrates that the warming trend in the temperature of the atmosphere in North America tends to be less in the areas with the greatest PM concentration levels, especially sulfates. The figure shows that long-term average temperatures in the North Atlantic region have decreased while the average temperatures have increased over most of Canada and the United States, with the greatest increases over the central plains of Canada and the arctic regions. Temperatures have remained constant or have cooled slightly in most of the southern part of the United States and northern Mexico. Comparing Figure 9.8 with Figure 9.2 reveals that there is a tendency for temperature increases to have been greatest in areas with relatively good visibility (i.e., low particulate matter levels) and less in areas with poorer visibility (such as the southeastern United States).

Many of the issues that are important to, and being addressed by, the radiation-balance community are identical or similar to those that are important to the description of horizontal visibility. There are important differences, however. Light scattering and absorption both degrade visibility. Absorption tends to contribute to warming (as indicated by the black carbon portion of the fossil fuel bar in Figure 9.7). The direct effect of light scattering is cooling (as reflected in the sulfate, organic carbon, and biomass burning bars), albeit by a small amount compared to the warming effect of greenhouse gases. Therefore, strategies to mitigate visibility impairment may not offer benefits in mitigating climate change. Since the most severe visibility effects tend to occur on scales that are relatively localized compared to the overall geographic scale of the global radiation balance, it should be possible to develop pollution-management strategies that take into account both visibility and radiation balance, but attention will have to be paid to developing an integrated strategy.

Table 9.2, which summarizes the responses of climate and visibility to changes in emissions of various pollutants, illustrates the areas where the climate and visibility responses differ. (See Table 3.2 for similar assessment of responses in other air-quality metrics.)

Emission-inventory activities in support of continental or global outlook analysis and strategy development are underway at the international level. Examples of inventory analysis include those by the Canada-U.S. Air Quality Agreement, the North American Free Trade Agreement (NAFTA) environmental protocols, the United Nations Economic Commission for Europe, and the Great Lakes Water Quality Agreement, as well as the IPCC. These inventories are also of benefit to understanding the background level of haze.

The IPCC (2002) document makes five specific recommendations directed at the atmospheric aerosol issue, which are paraphrased below. They may benefit the air-pollution community in North America as well.

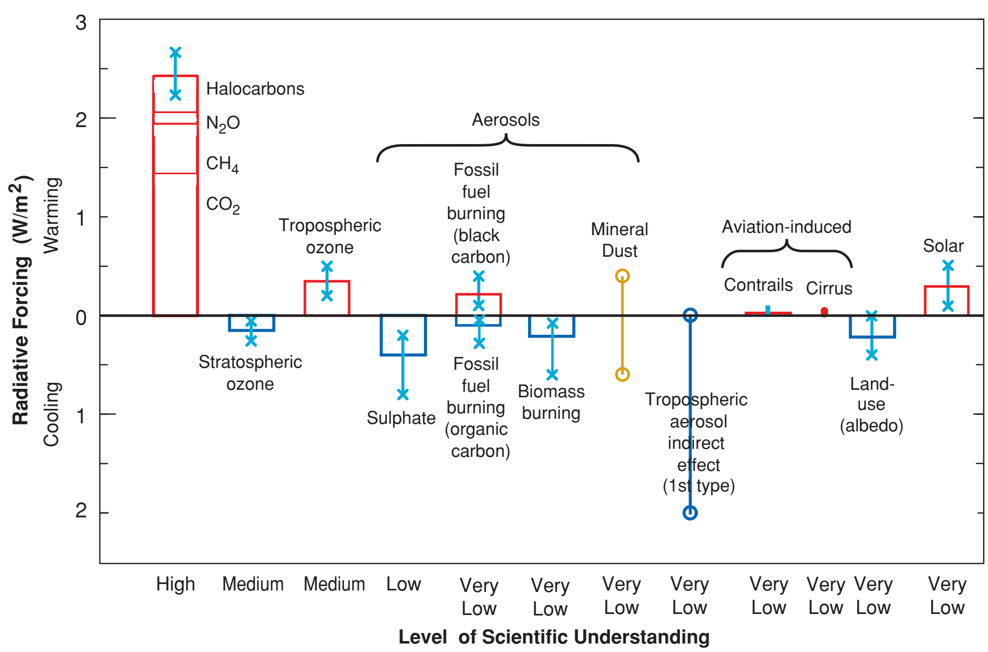


Figure 9.7. Global, annual mean radiative forcings (W/m^2) for the period from pre-industrial (1750) to the present. The height of each rectangular bar denotes a best estimate value while its absence denotes no best estimate is possible. The vertical line about the rectangular bar with "x" delimiters indicates an estimate of the uncertainty range. A vertical line without a rectangular bar and with "o" delimiters denotes a forcing for which no central estimate can be given owing to large uncertainties. A level of scientific understanding is accorded to each forcing, with H, M, L and VL denoting high, medium, low and very low levels, respectively. The figure shows that the dominant effect of atmospheric particles is a negative forcing (i.e., cooling). (IPCC, 2002; reproduced with permission).

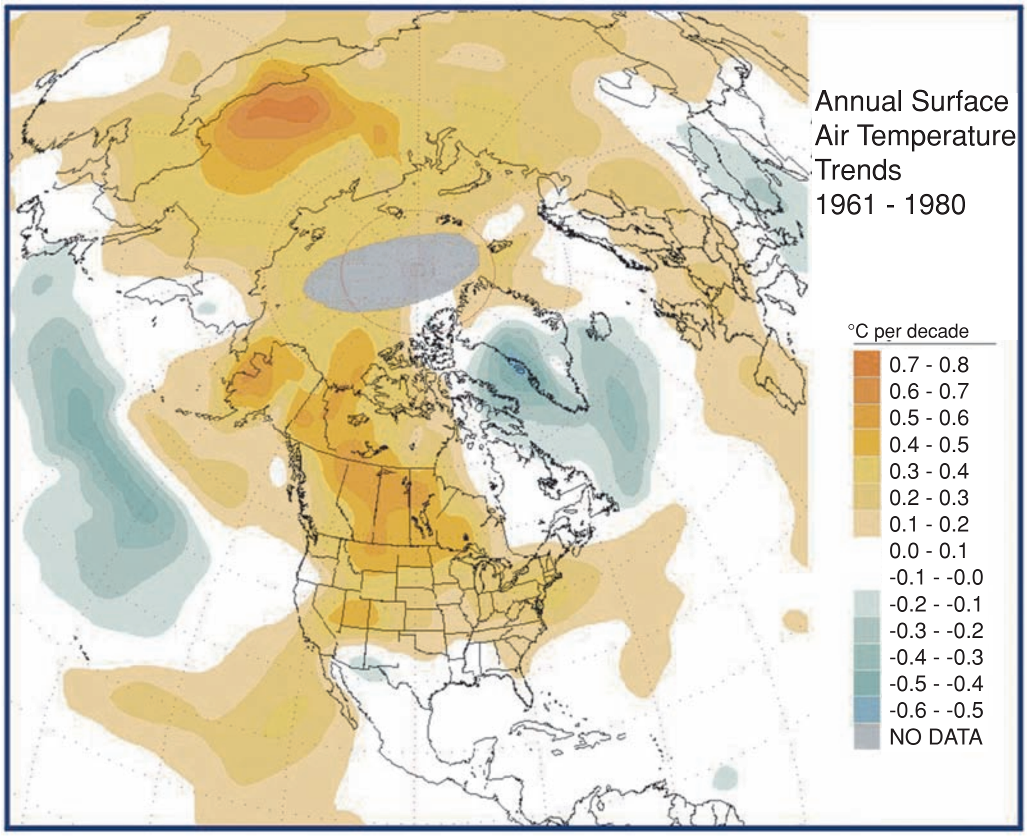


Figure 9.8. Measured change in annual surface air temperature 1961-1980. (Environment Canada, 1995).

Table 9.2. Responses of regional haze and climate to reductions in the emissions of secondary PM precursors and primary PM from present-day levels.

	Change In Associated Issue	
Pollutant Emitted	**Regional Haze**[(a)]	**Climate Impact**[(c)]
SO_2	↓	↑
NO_x	↑↓ [(b)]	↑↓
VOC	↑↓ [(b)]	↑↓
NH_3	↓	↑ [(d)]
Black Carbon	↓	↓
Primary Organic Compounds	↓	↑
Other primary PM (crustal, metals, etc.)	↓	↑

[a] Direction of arrow indicates increase (↑) or decrease (↓) and color signifies undesirable (red) or desirable (blue) impact; size of arrow signifies magnitude of change. Small arrows signify possible or small change.
[b] No change if little NH_3 available in atmosphere.
[c] Direct effects only; indirect effects through clouds and precipitation are highly uncertain. Note that the extent and possibly the scale of climate impacts for listed pollutants is quite different from those for CO_2 and CH_4, Direction of arrow indicates warming ↑ or cooling ↓.
[d] More accurately, decreased aerosol-induced cooling

1. Countries of the world need to develop and support a network of systematic ground-based observations of physical and chemical properties of atmospheric aerosols that are closely coordinated with satellite observations of aerosols.

2. Measurements of size-segregated PM physical, chemical, and optical properties are required through the atmospheric profile.

3. Characterization of aerosol processes through integrated experiments is needed in specified locations to quantitatively constrain models of aerosol dynamics and chemistry.

4. Studies to elucidate the indirect forcing of aerosols through solid understanding of cloud and precipitation processes are needed for development of a detailed microphysical representation of clouds for atmospheric models.

5. Measurements of aerosol characteristics from space could yield measurements of aerosol optical depth over land, reducing the uncertainties in current aerosol models.

Several examples illustrate the benefit of the interplay between research on visibility and radiation balance. For instance, although the radiation-balance work is more concerned with the distribution of aerosols through the depth of the atmosphere, the characterization of the transport of aerosols across the boundary layer means that information is also available on the layer or layers nearest the earth's surface, where visibility is an issue. Also, models that produce descriptions of regional particle burdens and atmospheric measurements of mass concentration, scattering and absorption coefficients, and water-uptake effects have direct implications for both radiation balance and visibility. Furthermore, global climate models are employing the calculation of optical properties from size distributions (Vignati et al., 2000), a process that is also of interest for visibility modeling.

Because of such linkages, enhanced scientific interactions between the radiation-balance and atmospheric-visibility communities would be of benefit to both communities. Such interactions could include coordinated measurement and modeling programs and joint scientific conferences (such as the specialty conferences held about once every three years under the joint sponsorship of the Air & Waste Management Association and the American Geophysical Union).

9.5 VISIBILITY MANAGEMENT ISSUES AND APPROACHES

9.5.1 What Is Being Done to Manage Visibility?

Management of air quality for the purpose of controlling visibility is being handled differently in the three North American countries. Of the three countries, the United States has the most advanced program for visibility management. Visibility has been formally recognized as an air-quality resource in several states, starting with an ambient air-quality standard for visibility in California in 1971. That standard was set at a level intended to protect visibility in the most polluted urban areas.

An organized nationwide strategy for managing visibility in Class-I areas (national parks and wilderness areas) was initiated with the U.S. Clean Air Act Amendments of 1977, which set a national goal of eliminating anthropogenic visibility impairment in those areas and established procedures for assessment of visibility as an "air-quality related value." Regulations adopted by the U.S. EPA in 1980 established procedures for determining and mitigating plume blight from single sources or small groups of sources. The scope of the visibility program was expanded substantially in 1999, when the U.S. EPA promulgated regulations intended to mitigate regional haze at Class-I areas over a period of 65 years.

In addition, protection of visibility in other areas, including cities, is an objective of a secondary (i.e., non-health) National Ambient Air Quality Standard for $PM_{2.5}$ (which is currently at the same level as the primary, health-protective standard).

Canada relies on its environmental-impact assessment process, outlined in the Canadian

Environmental Assessment Act, to address visibility impacts. This is generally applied in a source-by-source manner, but recently efforts have been made to accommodate regional approaches in areas such as the Oil Sands Region of northern Alberta and the diamond mining operations in the Northwest Territories. A first nationwide assessment of visibility impacts due to particulate matter in Canada has just been completed (McDonald, 2002).

Formal programs for mitigating either rural or urban visibility impairment have not been developed in Mexico. Visibility is being used as an indicator of progress in ongoing programs to improve air quality in Mexico City, however.

9.5.2 Alignment of Visibility and PM Control Programs

For the public, the ability to see through the atmosphere is perceived as an indicator of good air quality. Consequently, control programs for PM mass may benefit by considering the improvement of visibility as a public measure of success. Tracking improvements in visibility is one way that jurisdictions have of demonstrating improvement in particulate pollution. This immediate measure of progress is considerably more accessible and uncomplicated than human-health indicators, but the integrity of visibility as an indicator of progress relies on the PM-control program addressing the size fraction of particles that is assumed to affect health.

There is one situation where the linkage between the management of PM for health and for visibility may not be as straightforward. Strategies required to protect visibility on the clearest 20 percent of days in national parks and wilderness areas, as required by the U.S. regional-haze program, may be different than those required for protection of human health. One hurdle will be the impression that money is being spent to improve air quality at times when it is already pristine and is not likely to be adverse to health.

Because of the close linkage between $PM_{2.5}$ and visibility, air-pollution programs to address both are likely to be more efficient and successful when they operate in a coordinated fashion. As a specific example, the U.S. Congress has required that the programs for implementing the 1997 National Ambient Air Quality Standards for PM and the 1999 Regional Haze Rule be synchronized in time, principally to reduce the administrative and financial burdens on the states and on the owners of pollution sources.

In Canada, the management of visibility is not as closely coordinated with the management of PM. Environment Canada has the responsibility to ensure that transboundary issues, including both PM and visibility, are addressed under the Canadian Environmental Protection Act. Heritage Canada's Parks Service shares responsibility for managing visibility issues within the National Parks system, while the provincial governments are generally responsible for other air issues under the Canadian Environmental Assessment Act. Coordination with regard to visibility issues, similar to that in the United States, is not available nationally, but has taken place in localized settings, such as Kejimkujik National Park and the Lower Fraser Valley around Vancouver, British Columbia.

It is important to note that the levels of fine-particle mass concentrations established as air-quality management standards for the protection of health may not be effective for protecting or improving scenic visibility. Specifically, meeting the U.S. 24-hour $PM_{2.5}$ ambient standard of 65 mg/m^3 will enhance visibility in only a few areas. Visual range in some eastern major urban centers and much of California will benefit by achieving the 24-hour standard. In other areas the standard is higher than currently observed mass concentrations, hence visibility will not be improved unless the particulate-matter load is reduced even though it already achieves the level of the standard. The number of places where visibility will be improved by meeting the annual $PM_{2.5}$ ambient standard of 15 mg/m^3 is slightly larger, but again these sites are found predominantly in the eastern states and California. In general, the national standards for $PM_{2.5}$ are not going to contribute significantly to the improvement or protection of visibility in much of the United States.

In Canada, most locales experience 24-hour mass concentrations at or above the 30 $\mu g/m^3$ Canada-Wide Standard level only occasionally. The 98th percentile of mass measurements has potential to exceed the standard only in urban centers of the Golden Triangle and Upper Canada. Therefore, meeting the Canada-Wide Standard at these sites will improve local visibility to a small degree. However, for the rest of Canada, including all of the west and the Maritimes, maintaining the Canada-Wide Standard allows increasing the current PM mass concentrations and could produce a degradation in visibility (McDonald, 2002). Therefore, the Canada-Wide Standard for $PM_{2.5}$ does not promote the protection or improvement of visibility over much of the country. This is especially so for the most pristine regions, including national parks and wilderness areas.

9.5.3 Regional Planning Organizations

Because regional haze is a result of long-range transport and can cover several states or provinces, the United States has established five regional planning organizations for the purpose of performing the analyses and modeling needed to implement the regional haze rule. The concept of regional planning organizations for visibility originated with the Grand Canyon Visibility Transport Commission (GCVTC), which was prescribed by Congress in the Clean Air Act Amendments of 1990. The GCVTC, which encompassed 9 states in the western end of the country, took on a broader charter of assessing strategies for protecting visibility throughout the 16 Class-I areas of the Colorado Plateau, of which Grand Canyon National Park is one. A comprehensive regional air-quality model was developed and was applied to evaluate the visibility consequences of a variety of air-quality management options. The final product of the GCVTC was a report to the U.S. EPA with recommendations for an approach to air-quality management.

The GCVTC has been superseded by the Western Regional Air Partnership (WRAP), which is actively engaged in formulating an air-quality management program for 13 states; it is framed around the GCVTC recommendations and conforms to the subsequent Regional Haze Rule. Four other regional planning organizations have been formed to perform similar functions over the rest of the country.

In addition to the regional planning organizations, other regional consortia have performed visibility research and attribution analyses over multi-state regions. A notable example is the Southern Appalachian Mountains Initiative (SAMI), which addressed visibility as one of its concerns.

9.5.4 Point-Source Control Programs

Section 9.2.1 described several short-term studies that were concerned with the contributions of electric-power generating stations to visibility impairment at Class-I areas or, in one case, in an urban area. The emission controls that have been installed, or will be installed, are the first examples of the management of visibility impairment attributable to point sources. (Although the emissions of a single source are involved, these were not the typical cases of plume blight, because long transport distances were involved and secondary pollutants were the dominant concern.) Each of these instances involved a field-measurement and air-quality modeling study that cost many millions of dollars.

The Regional Haze Rule prescribes that the visibility effects of many major sources be assessed and the feasibility of applying Best Available Retrofit Technology be evaluated. It does not seem feasible to carry out a major field program and modeling study for each of these facilities, so less data- and resource-intensive means of making these assessments are needed.

9.5.5 International Programs

Some cooperative efforts at studying PM and visibility have occurred along the U.S.-Canadian border and the U.S.-Mexican border. The joint U.S.-Canadian efforts have addressed 1) a pair of contiguous national parks across the border from each other, the Waterton Lakes (Alberta) and Glacier (Montana) National Parks, and 2) the Acadia National Park in Maine (Hoff et al., 1997).

A joint U.S.-Mexican effort studied visibility-related PM on both sides of the border in the vicinity of Big Bend National Park in Texas (Big Bend Air Quality Work Group, 1999). A subsequent study to apportion the observed aerosol and visibility impairment to sources in the two countries (the BRAVO Study, described in Table 9.1) has been carried out without Mexican participation, however.

Although trans-boundary transport of air pollution is known to occur, no actions have yet been taken to regulate emissions in one country for the purpose of mitigating visibility impairment in another country. However, Canada and the United States have signed an Air Quality Accord that includes provisions for each nation to consider the transboundary impact of air pollution on pristine sites in the other country and to implement any needed controls by 2010. To the south, the GCVTC analyses, the BRAVO Study, and other studies have investigated transport of visibility-related pollutants between the United States and Mexico through the modeling of transport fluxes.

9.6 SUMMARY AND CONCLUSIONS

Fine particles in the atmosphere are not individually visible to the human eye, but their presence is visible through their contribution to the hazy appearance of polluted air and the impairment of visibility. The effects of particles on visibility can be described theoretically or using empirical relationships, given the chemical composition and physical characteristics of the aerosol derived from measurements or application of a mathematical model. Particles also affect the radiation balance of the earth through mechanisms of light scattering and absorption similar to those that affect visibility, as well as through indirect mechanisms that involve the influence of PM on clouds.

Most of the particles of importance to visibility and the earth's radiation balance are secondary particles. These are formed in the atmosphere through physical and chemical processes involving gaseous precursors – both natural and anthropogenic. The optical effects of particles depend primarily on size and chemical composition, and secondary particles tend to be of the size range (particle diameters of 0.3 to 1.0 µm) that is most effective at scattering visible light. Relative humidity is a particularly important atmospheric factor, since particle light scattering at high relative humidity is many times that of the dry aerosol for hygroscopic species, such as sulfates, nitrates, and some organics. Much of the current understanding of relationships between PM and visibility comes from a broad range of short-term field studies at both urban and pristine locations and from the long-term IMPROVE monitoring program. Most studies have taken place in the United States, some have occurred along the southern tier of Canada, a few have taken place in Mexico City, and one has included measurements in northeastern Mexico. Consequently, visibility and its relationship to PM are currently best characterized in the United States.

These studies demonstrate that the spatial distribution of light extinction (the sum of light scattering and absorption) generally matches that of fine PM concentration, except that a given PM concentration causes greater extinction in a very humid environment than in a dry environment. Consequently, outside of urban areas, extinction tends to be greatest (and visibility poorest) in the eastern portions of Canada and the United States. Visibility is best in the arid intermountain portion of the western United States. Also, because of declining fine-particle concentrations throughout much of the United States, visibility has been improving in most areas during the past two decades. Because of the lack of data, trends in Canada and Mexico are not known.

Formulas that represent light extinction as the sum of weighted chemical concentrations are useful for estimating the optical effects of the aerosol. Each concentration, derived from measurements or modeling, is multiplied by an empirical scaling factor that represents the light scattering or absorption efficiency of that chemical species. More rigorous calculations of light extinction, based on theoretical descriptions of the interaction of light with particles, require further information about the size distribution of the particles (either from specialized measurements or from advanced aerosol models) and are computationally more demanding.

Based on such analyses, non-urban visibility impairment in eastern North America is predominantly due to $SO_4^=$ particles, with organic particles generally second in importance. In the West, the contributions of $SO_4^=$ and OC are comparable, and NO_3^- plays a significant role in the populated areas of California. Carbonaceous material, either OC or BC, is an important contributor in some urban areas of North America. Soil particles can be important contributors to visibility impairment in areas susceptible to wind-blown dust.

These relationships suggest that efforts to mitigate visibility impairment will require control of emissions of different chemical species in different geographic areas. Also, because visibility in the clearest areas is sensitive to even minute increases in PM concentrations, strategies to preserve visibility on the clearest days may require stringent emission limitations,and dilute impacts from very distant sources can still be important.

Modeling of the visibility effects of PM is based on prediction of the aerosol composition by a PM chemical-transport model, which then is followed by the additional step of calculating light extinction by an empirical or theoretical formula. Thus the quality of the visibility prediction depends greatly on the skill of the PM model. As described in Chapter 8, models that predict secondary PM on a regional basis have significant limitations for some species, and the performance of the latest PM models has not yet been evaluated extensively. Consequently the quality of modeled representations of light extinction based on these PM calculations is currently somewhat uncertain.

The situation is similar with the modeling of the earth's radiation balance. Much remains to be learned about the important aerosol processes in the upper atmosphere and modeling appears to have significant uncertainties. Extensive work is underway to learn more about the particles and their characteristics and to improve models.

A major gap in knowledge is the role of organic compounds in particles important to visibility and the radiation balance. Currently all organic species are lumped into single category labeled "OC," although different organic compounds have varying degrees of reactivity, volatility, and solubility in water. There is a need to better characterize both the various constituents of the volatile organic compounds that are emitted from sources and the resulting organic PM, and to develop mechanistic theories that explain the transition. Furthermore, because of the importance of water uptake to light scattering, the hygroscopic behavior of the organic matter needs to be better explained.

Other enhancements are required for the PM modeling that underlies visibility calculations. As discussed in Section 8.10, the most important are an improved characterization of the meteorological field and refinements in emission inventories. For visibility, meteorological information that is especially important includes the wind and humidity fields and the descriptions of cloud locations and characteristics. Shortcomings in these areas have accounted for much of the error in recent efforts at modeling visibility impacts, both from isolated sources and for regional emission distributions.

Despite some gaps in understanding, uncertainties in characterizing visibility and the effects of PM management on it are significantly smaller than for other effects, such as human health and global climate change. Direct measurements of light extinction in the field are an independent check on methods to construct extinction from particle information or by other model approaches. In fact, visibility measurements have been used as a surrogate for PM measurements and provide a basis for evaluating regional PM models. In particular, the IMPROVE network has produced a consistent and long-term data set of PM composition that is not yet matched by others available for human-health and radiation-balance purposes. One should note, though, that deciphering a change in a small value (such as the visibility impairment in a pristine region) may cause more difficulties analytically and statistically than looking at trends in the elevated values of PM that are of relevance for health purposes

Data-quality control is important. Mundane issues such as missing observations impose challenges in calculating truly representative hourly, daily or annual values through averaging of instantaneous measurements, and appropriate uncertainties need to be defined as part of the data-analysis process. Questions about the spatial representativeness of measurements (typically at a point) or model endpoints (typically an average for a grid cell) provide perhaps the greatest uncertainty. Current air-quality management approaches that consider regional management zones are designed to reduce this uncertainty.

As with PM itself, research will be required over the long-term to decrease uncertainties in visibility-relevant fundamental science issues, such as the roles of size distributions, volatile organics, hygroscopic growth, and extinction efficiencies. The uncertainties resulting from lack of PM process understanding are potentially quite large, but again the ability to directly measure visibility provides the capability to test updated hypotheses as the science progresses.

Recognizing limitations in understanding and, specifically, in the ability to model visibility, the U.S. National Academy of Sciences concluded that existing knowledge and tools appeared to be adequate to develop strategies for managing visibility (NRC, 1993). On this basis, the United States has initiated a 65-year program for mitigating regional haze in national parks and wilderness areas. This regional-haze program is separately addressing the needed PM emission reductions in five regions of the country, with appropriate attention to transport between planning regions. The initial emission-management actions that may be implemented under that program are not likely to be very sensitive to uncertainties in current models. Better tools will be required to make the more sensitive and costly strategy decisions further downstream, in a few decades, but one can assume that the models and data will be improved by then.

Comparable programs to address visibility have not been proposed by Canada and Mexico, although efforts at limiting and reducing PM concentrations for health reasons can be expected to provide benefits to visibility. Furthermore, the measurement networks needed to characterize visibility and its trends nationwide do not exist in either country, so the visibility situation there is not well documented. The United States and Canada have agreed, though, to limit the transboundary impacts of air pollution (including effects on visibility) on pristine sites in the other country, which has beneficial visibility implications for near-border scenic areas in both countries.

9.7 POLICY IMPLICATIONS

The key points of this chapter and their policy implications are summarized below.

Visibility impairment is sensitive to the chemical composition of $PM_{2.5}$, and also depends strongly on ambient relative humidity. Secondary particles tend to be of the size range (diameters of 0.3 to 1.0 µm) that is most effective at scattering visible light. Relative humidity is a particularly important atmospheric factor, with light scattering of fine PM at high relative humidity being many times that of the dry aerosol. *Implication:* Controlling the precursors of secondary PM, especially the precursors of $SO_4^=$ and NO_3^-, will be effective in improving regional haze as these particles grow in relation to relative humidity.

Non-urban visibility impairment in eastern North America is predominantly due to $SO_4^=$ particles, with organic particles generally second in importance. In the West, the contributions of $SO_4^=$ and OC are comparable, and NO_3^- plays a significant role in the populated areas of California. In some urban areas across North America, BC is an important contributor. Soil particles can be important contributors to visibility impairment in areas susceptible to windblown dust. Wildfires, prescribed burning, and agricultural fires can be dominant episodic contributors to regional haze in all areas. *Implication:* Efforts to mitigate visibility impairment will require control of emissions of different chemical species in different geographic areas.

Visibility in the clearest areas is sensitive to even minute increases in PM concentrations. *Implication:* Strategies to preserve visibility on the clearest days may require stringent limitations on upwind emissions growth, and dilute impacts from very distant sources can be important.

Theoretical or empirical algorithms can be used to estimate visibility impairment attributable to measured PM concentrations of $SO_4^=$, NO_3^-, OC, BC, and soil at a specific relative humidity, although the estimates are more uncertain at extreme levels of relative humidity (> 90 percent). Modeling future visibility changes due to PM-concentration changes relies on the prediction of aerosol composition by a chemical-transport model (CTM), followed by the additional step of calculating light extinction using an empirical or theoretical formula. The quality of the visibility predictions is greatly dependent on the performance of the CTM. Currently this modeling has significant limitations for NO_3^- and carbonaceous PM species. *Implication:* Chemical-transport models can be used now for semi-quantitative projections of regional-haze improvements resulting from reductions in PM and PM precursors, with the caveat that the current quality of modeled representations of species concentrations is somewhat uncertain.

Particles affect the radiation balance of the earth through mechanisms of light scattering and absorption similar to those that affect visibility, as well as through indirect effects on clouds. While scattering and absorption both degrade visibility, they can have counterbalancing effects on the aerosol contribution to the radiative balance. Specifically, light absorption by particles tends to increase surface heating while light scattering by particles tends to decrease surface heating, although the direct effect is estimated to be small compared to the effects of greenhouse gases. The indirect effect may be larger, but is highly uncertain. *Implication:* Strategies for managing aerosol chemical-component concentrations to mitigate visibility impairment and to reduce aerosol forcing of climate change may not be wholly consistent, but the different spatial scales of haze and of climate-forcing aerosol mean that it should be possible to address both concerns with an integrated strategy.

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