

## CHAPTER 3

# SPATIAL DISTRIBUTIONS OF RECONSTRUCTED LIGHT EXTINCTION AND LIGHT-EXTINCTION BUDGETS

The model used to reconstruct the light extinction coefficient from aerosol measurements and to derive the reconstructed light extinction coefficient and other visibility metrics for the sites are presented and examined here. Using this model, the relative contribution of various aerosol components to total light extinction is combined into light-extinction budgets for the regions described in Chapter 1.

### 3.1 RECONSTRUCTING LIGHT EXTINCTION FROM AEROSOL MEASUREMENTS

The light-extinction coefficient,  $b_{ext}$  (expressed as inverse megameters, 1/Mm), is the sum

$$b_{ext} = b_{scat} + b_{abs} = b_{sg} + b_{sp} + b_{ag} + b_{ap} \quad (3.1)$$

where  $b_{scat}$  is the sum of scattering by gases and scattering by particles, and  $b_{abs}$  is the sum of absorption by gases and particles. Scattering by gases in the atmosphere,  $b_{sg}$ , is described by the Rayleigh scattering theory [vandeHulst, 1981] and will be referred to as Rayleigh scattering. The IMPROVE program assumes a standard value of 10 1/Mm. Scattering by particles,  $b_{sp}$ , is caused by both fine and coarse aerosol species and is the largest contributor to total light extinction in most locations [Malm et al., 1994a]. Absorption due to gases,  $b_{ag}$ , is primarily due to nitrogen dioxide (NO<sub>2</sub>) and is assumed to be negligible because almost all monitoring sites are in rural locations [Trijonis and Pitchford, 1987]. Absorption by particles,  $b_{ap}$ , is caused primarily by carbon containing particles.

A particle in the atmosphere can be a mix (internal mixture) of various aerosol species, or in some cases its compositional structure may be restricted to one species (external mixture) such as (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>. Furthermore, an internally mixed aerosol such as organic/sulfate/water particle can be externally mixed from wind-blown dust particles. Whether an aerosol is internally or externally mixed, it scatters and/or absorbs a specific fraction of radiant energy impinging on it. Following the suggestion of White [1986], an aerosol scattering/extinction per unit mass ratio will be referred to as specific scattering/extinction, as in specific gravity.

Most routine aerosol monitoring programs and many special study visibility characterization programs were designed to measure bulk aerosol species mass concentrations such as sulfates, nitrates, carbonaceous material, and selected elements [Heisler et al., 1980; Malm et al., 1994b; Tombach and Thurston, 1994; Watson et al., 1990; Macias et al., 1981]. They were not designed to determine the microphysical and chemical characteristics of these species.

The inherent limitations of estimating aerosol optical properties from bulk aerosol measurements have been addressed, at least in part, by a number of authors. For instance, Ouimette and Flagan [1982] have shown, from basic theoretical considerations, that if an aerosol is mixed externally or if in an internally mixed aerosol the index of refraction is not a function of composition or size, and the aerosol density is independent of volume, then:

$$b_{ext} = \sum_i \alpha_i m_i \quad (3.2)$$

where  $\alpha_i$  is the specific scattering or absorption efficiency and  $m_i$  is the mass of the individual species.

Malm and Kreidenweis [1997] demonstrated from a theoretical perspective, that specific scattering of mixtures of organics and sulfates were insensitive to the choice of internal or external mixtures. Sloane [1983, 1984, 1986], Sloane and Wolff [1985], and more recently Lowenthal et al. [1995], Malm [1998], and Malm et al. [1997] have shown that differences in estimated specific scattering between external and internal model assumptions are usually less than about 10%. In the absence of detailed microphysical and chemical structure of ambient aerosols, the above studies demonstrate that a reasonable estimate of aerosol extinction can be achieved by assuming each species is externally mixed.

However, the issue of water uptake by hygroscopic species must be addressed. Implicit to the use of Equation (3.2) is an assumed linear relationship between aerosol mass and extinction. It is well known that sulfates and other hygroscopic species form solution droplets that increase in size as a function of relative humidity (RH). Therefore, if scattering is measured at various relative humidities the relationship between measured scattering and hygroscopic species mass can be quite nonlinear. A number of authors have attempted to linearize the model, in an empirical way, by multiplying the hygroscopic species by such a factor as  $1/(1-RH)$  to account for the presence of water mass [White and Roberts, 1977; Malm et al., 1986]. However, Malm et al. [1989] and Gebhart and Malm [1989] proposed a different approach. They multiplied the hygroscopic species by a relative humidity scattering enhancement factor,  $f(RH)$ , that is calculated on a sampling-period-by-sampling-period basis using Mie theory and an assumed size distribution and laboratory measured aerosol growth curves.

Measurements of hygroscopic species growth as a function of relative humidity show that species such as ammonium sulfate show zero growth until a relative humidity, referred to as the deliquescent relative humidity, is reached where they spontaneously form a solution droplet that is in equilibrium with water molecules in the ambient atmosphere. Conversely, when the relative humidity is decreased from some value greater than 80% the solution droplet retains water below the deliquescent point to a relative humidity where all water is spontaneously given up. This point is referred to as the crystallization relative humidity.

However, because the growth factor and light-scattering efficiency for ambient aerosols has previously been observed to be rather smooth, [Sloane 1983, 1984, 1986; Wexler and Seinfeld, 1991; Waggoner et al., 1981; Day et al., 2000; Malm et al. 2000] a “best estimate” for the sulfate and nitrate species growth, the laboratory growth curves, as measured by Tang [1996] were smoothed between the deliquescence and crystallization points. Malm [1998] and Malm et al., [1997] have demonstrated that in both the East (Great Smoky Mountains National Park) and West (Grand Canyon National Park) the best estimate growth model, in combination with measured size distributions, yields an  $f_T(RH)$  function that results in good agreement between measured and reconstructed scattering for particles less than 2.5  $\mu\text{m}$ .

Therefore, the following equation is used to estimate reconstructed particle scattering:

$$\begin{aligned}
 b_{scat} = & (3)f_T(RH)[SULFATE] \\
 & + (3)f_T(RH)[NITRATE] \\
 & + (4)f_{org}(RH)[OMC] \\
 & + (1)[SOIL] \\
 & + (0.6)[CM]
 \end{aligned}
 \tag{3.3}$$

The brackets indicate the species concentration, 3  $\text{m}^2/\text{g}$  is the dry specific scattering for sulfates and nitrates, 4  $\text{m}^2/\text{g}$  for organic carbon, and 1  $\text{m}^2/\text{g}$  and 0.6  $\text{m}^2/\text{g}$  are the respective scattering efficiencies for soil and coarse mass. The efficiencies for fine soil and coarse mass are taken from a literature review by Trijonis and Pitchford [1987].

A dry scattering efficiency of 3  $\text{m}^2/\text{g}$  is a nominal scattering efficiency based on a literature review by Trijonis et al. [1988, 1990] and a review by White [1990]. Trijonis' best estimate for sulfates and nitrates is 2.5  $\text{m}^2/\text{g}$  with an error factor of 2, while for organics it is 3.75  $\text{m}^2/\text{g}$  again with an error factor of 2. White took a somewhat different approach in that he reviewed 30 studies in which particle scattering and mass were measured. He then estimated a high and low scattering efficiency by using mass measurements to prorate the measured extinction. For sulfate, the low estimate was arrived at by assuming sulfate, nitrate, and organics scatter twice as efficiently as all other species, and for the high estimate he assumed that only sulfate was twice as efficient. His low and high sulfate mass scattering efficiencies for the rural west were 3.0 and 3.7  $\text{m}^2/\text{g}$ , respectively. For organics his low estimate assumes organics and other non-sulfate species scatter half as efficiently as sulfates, and for the high estimate he assumes organics are three, and sulfates twice as efficient at scattering light as other species. His low and high estimates for organic mass scattering coefficients are 1.8 and 4.1  $\text{m}^2/\text{g}$ . More recently, Malm et al. [1996] demonstrated that an assumption of dry specific scattering values given in Equation (3.3) yielded good agreement between measured and reconstructed extinction across the entire IMPROVE monitoring network.

Various functions for the hygroscopicity of organics have been proposed. Assumptions must not only be made about the solubility of organics but also on the fraction of organics that are soluble. It should be noted, models that treat water uptake for nonideal multicomponent solutions using theoretical and semi-theoretical thermodynamic relationships have been

developed and have been applied to both visibility and climate forcing problems [Saxena and Peterson, 1981; Pilinis et al., 1995; Saxena et al., 1986, 1993]. The correct treatment of the hygroscopicity of species in multicomponent mixtures—especially organic species—remains problematic, not only because of the lack of suitable mixture thermodynamic data but also because of the lack of information about other critical mixture properties. Given the variety of organic species, it is possible that a geographic variation in organic species exists, with large fractions of soluble species occurring in certain parts of the continent and much smaller fractions in other areas. However, field experiments and subsequent data analysis at Great Smoky Mountains and Grand Canyon National Parks [Malm et al., 1997; Malm and Kreidenweis, 1996; Malm et al., 2000] and, more generally, data collected in the IMPROVE Network [Malm et al., 1996] show that to within the uncertainty of the measurements and modeling assumptions, organics are not or are only weakly hygroscopic. Therefore,  $f_{org}(RH)$  for organics was set equal to one.

Equation (3.3) has been shown to give a good estimation of scattering for particles less than 2.5  $\mu\text{m}$ , however, estimating extinction requires a knowledge of particle absorption. Mass absorption efficiencies of carbon vary by more than a factor of two as do direct measurements. Horvath [1993] has reviewed the measurement of absorption, while Fuller et al. [1999] has theoretically explored the variability of absorption efficiency as a function of carbon morphology. Although absorption can be estimated in a variety of ways, there is no one method that is generally accepted by the scientific community. For purposes of this report, carbon absorption is estimated using:

$$b_{abs} = 10[LAC] \quad (3.4)$$

where  $b_{abs}$  is particle absorption, LAC is the concentration of light-absorbing carbon as measured using the Thermal Optical Reflectance (TOR) analysis scheme [Chow et al., 1993], and 10 is the specific absorption for LAC, which has been used by a number of scientists [Horvath, 1993].

Because aerosol concentrations are derived from averages over long periods, the light scattering due to soluble species is derived using hourly RH values less than or equal to 98%, as given by the following equation:

$$b_{scat} = \alpha F_T \bar{C}, \quad (3.5)$$

where  $\bar{C}$  is the average species concentration,  $\alpha$  is the specific scattering, and

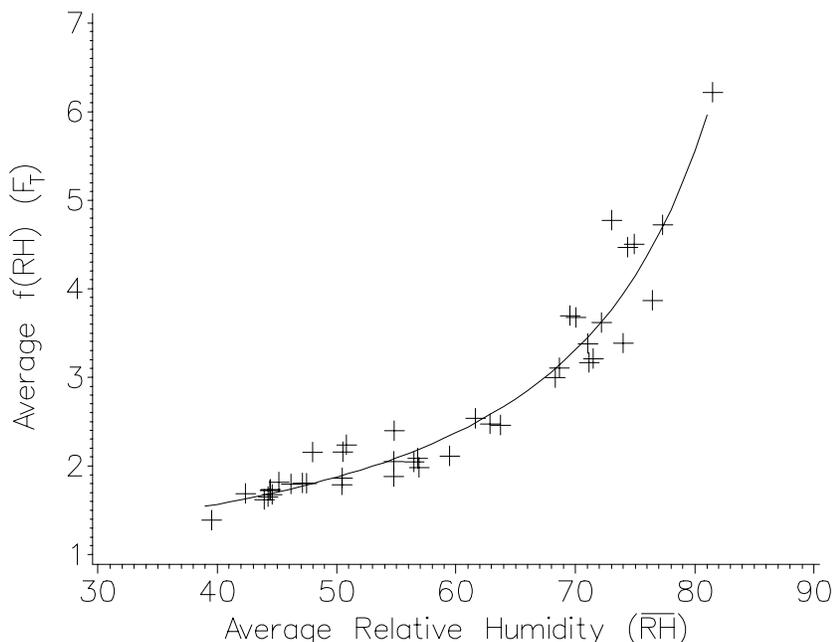
$$F_T = \overline{f_T(RH)}. \quad (3.6)$$

Using Equation (3.3), extinction budgets for a time interval may be calculated by replacing  $f_T(RH)$  with  $F_T$  and by using the average concentration of each species over the same time interval as the mass concentration.

Using the data from sites with collocated optical and RH data, a polynomial curve was fitted to the annual and seasonal data as defined by

$$F = b_0 + b_1(100/(100 - \overline{RH})) + b_2(100/(100 - \overline{RH}))^2 \quad (3.7)$$

where  $b_0 = 0.33713$ ,  $b_1 = 0.58601$ , and  $b_2 = 0.09164$  with an R-square of 0.93 annually. Figure 3.1 shows the fitted curve plotted against annual average RH for IMPROVE sites with collocated RH data. Table 3.1 lists the regression results for annual and seasonal averaging periods. For those sites without collocated optical and RH data, the annual factors can be calculated using Equation (3.7) and estimates of annual average RH. (Five significant figures are used in the curve fit program used for this report and therefore are included here for reference.)

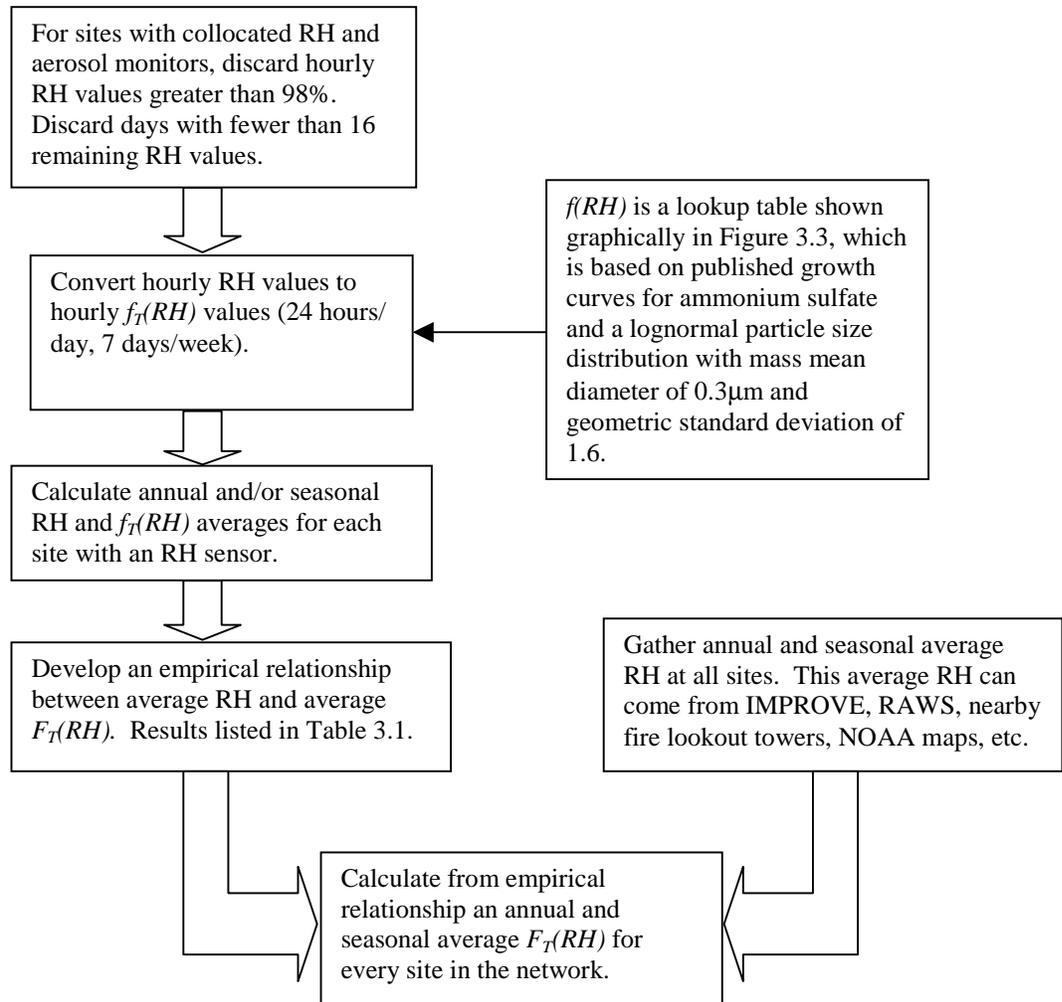


**Figure 3.1** Best-fit relation between a site's annual average RH and its annual average RH correction factor.

**Table 3.1** Parameters of the best-fit equation relating the relative humidity light-extinction correction factors ( $F_T$ ) to seasonal and annual average site relative humidity ( $F = b_0 + b_1/(1-RH) + b_2/(1-RH)^2$ ).

Season	$b_0$	$b_1$	$b_2$	$R^2$
Spring	-0.01097	0.78095	0.080147	0.93
Summer	-0.18614	0.99211	---	0.91
Autumn	-0.24812	1.01865	0.01074	0.93
Winter	0.34603	0.81984	---	0.77
ANNUAL	0.33713	0.58601	0.09164	0.93

Figure 3.2 is a flowchart, which details the process used to account for the effects of relative humidity at those sites with or without relative humidity sensors.



**Figure 3.2** The process by which IMPROVE data is used to develop site specific seasonal and annual RH correction factors.

The extinction reconstruction process starting with the raw IMPROVE data through to the extinction calculation can be summarized:

- (1) At those sites with collocated RH sensors and particle monitors, discard hourly RH values greater than 98% and discard days with less the 16 RH values.
- (2) Convert the hourly RH to  $f(RH)$  values using the “smoothed” ammonium sulfate  $f_T(RH)$  versus RH lookup table shown graphically in Figure 3.3.
- (3) Calculate annual and/or seasonal RH and  $f(RH)$  averages ( $F_T$ ) (Equation (3.6)).
- (4) Develop an empirical relationship between average RH and average  $F_T(RH)$  (Equation (3.7)).

- (5) For the desired time period (annual or seasonal) find the average of the following species: sulfate, nitrate, organics, light-absorbing carbon, fine soil, and coarse mass.
- (6) Using these averages calculate average reconstructed aerosol extinction according to the equation:

$$\begin{aligned}
 b_{ext} = & (3)F_T(RH)[SULFATE] \\
 & + (3)F_T(RH)[NITRATE] \\
 & + (4)[OMC] \\
 & + (10)[LAC] \\
 & + (1)[SOIL] \\
 & + (0.6)[CM]
 \end{aligned}
 \tag{3.8}$$

where the parameters enclosed in the brackets are the average concentrations of each species.

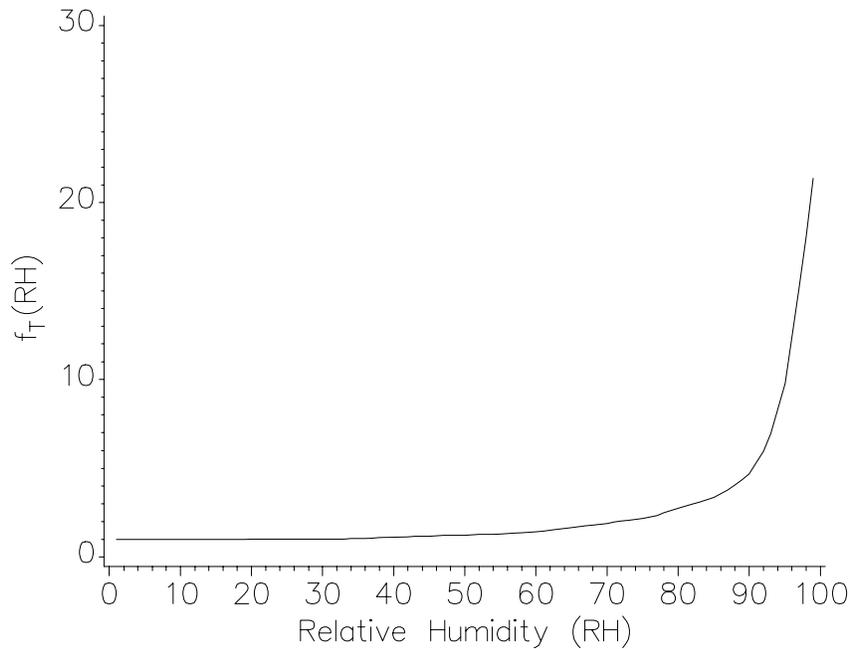
The use of a 98% RH cutpoint is somewhat arbitrary, but it was chosen to allow for the likelihood that above 98%, precipitation would obscure visibility without regard to pollutant concentrations, and as an expedient measure because  $f_T(RH)$  is infinite at 100% RH. The same  $f_T(RH)$  was used in the first and second IMPROVE reports [Sisler et al., 1993; Sisler, 1996]. However, the assumptions used for estimating this curve will be investigated in light of more recent growth and particle size distribution data.

There are two ways reconstructed extinction is calculated in this report that are different from the 1996 IMPROVE report. First, the factor  $f(RH)$  that accounts for the relative humidity effects on hygroscopic aerosols has been upgraded with new relative humidity data from additional relative humidity monitoring sites and second, absorption is estimated from measurements of light-absorbing carbon rather than from transmission measurements of filter media. Therefore, some differences in aerosol extinction between this and the 1996 report are due to changes other than levels of aerosol mass concentration.

Visibility expressed as reconstructed deciview (dv) can now be calculated. The deciview is a visibility metric based on the light-extinction coefficient that expresses incremental changes in perceived visibility [Pitchford and Malm, 1994]. Because the deciview expresses a relationship between changes in light extinction and perceived visibility, it can be useful in describing visibility trends. A 1-dv change is about a 10% change in extinction coefficient, which is a small but perceptible scenic change under many circumstances. The deciview is defined by the following equation:

$$dv = 10 \ln(b_{ext} / 10)
 \tag{3.9}$$

The deciview scale is near zero for pristine atmosphere ( $dv = 0$  for Rayleigh condition at about 1.8 km elevation) and increases as visibility is degraded.



**Figure 3.3** *RH factors ( $f_T(RH)$ ) derived from Tang's ammonium sulfate growth curves smoothed between the crystallization and deliquescence points.*

## 3.2 RECONSTRUCTED LIGHT EXTINCTION AND LIGHT-EXTINCTION BUDGETS

Spatial patterns in the reconstructed light extinction are similar to those observed for aerosols since reconstructed light extinction is calculated from aerosol concentrations. However, because specific scattering of sulfates and nitrates are larger than other fine aerosols because of associated water, light-absorbing carbon has relatively high specific extinction, and coarse particle scattering contributes to total aerosol extinction, the extinction budgets are somewhat different from fine aerosol budgets.

### 3.2.1 Characteristics of the Regions

Tables 3.2, 3.3, and 3.4 summarize the seasonal and annual averages of the reconstructed light extinction coefficients for each of the 20 regions in the United States averaged over three years, March 1996 through February 1999.

Table 3.2 shows the breakdown of extinction among fine and coarse particle scattering and light absorption. In addition, this table shows the percentage of total light extinction (including Rayleigh scattering) that is caused by aerosol light extinction (both scattering and absorption). Also, the average relative humidity for each region is reported. Table 3.3 shows the aerosol light extinction as well as the contributions of sulfate, nitrate, organic carbon, light absorption, and coarse particles (including fine soil). Table 3.4 shows the aerosol light-extinction budgets: the fractions (percent) of

total aerosol (non-Rayleigh) light extinction contributed by sulfate, nitrate, organic carbon, light absorption, and coarse particles (including fine soil).

The characteristics of each region are briefly discussed.

Alaska. The Alaska region consists only of the measurements at Denali National Park and Preserve. The three-year annual average extinction is 20 1/Mm, of which aerosol extinction constituted 50%. The seasonal variation is small and varies from a low of 17.9 1/Mm in the winter to a high of 22.3 1/Mm in the summer. However, the extinction attributable to nitrate and organics show significant seasonal variation. Nitrate extinction ranges from a low of 0.3 1/Mm in the summer to a high of 0.8 1/Mm in the winter. Organic extinction, on the other hand, is highest in the summer at 5.5 1/Mm and lowest in the winter at 1.2 1/Mm. Sulfate is the largest contributor to aerosol extinction at an annual average of 38.9% and ranges from a seasonal high in the spring of 46.8% to a summer low of 28.2%. The next largest contributor is organics at a seasonal average of 27% ranges from a summer high of 44.4% to a winter low of 15.8%. The remaining contributors on an annual basis in order of importance are, soil and coarse particles (both at 19.9%), light-absorbing carbon (9.7%), and nitrate (4.5%).

Appalachian Mountains. This region consists of Dolly Sods Wilderness Area in West Virginia, Shenandoah, Great Smoky Mountains National Parks, and Shining Rock Wilderness Area in North Carolina. With an annual extinction of 98.5 1/Mm this region is typical of many eastern rural venues. The seasonal variation of extinction is about a factor of 3, ranging from 61 1/Mm in the winter to 169 1/Mm during summer. The seasonal variation is almost entirely due to sulfate extinction, which varies by a factor of 4 from 34.6 1/Mm in the winter to 136.3 1/Mm in the summer. Similarly, extinction due to organics, which averages 9.4 1/Mm annually, varies from a winter low of 6.8 1/Mm to 12.5 1/Mm during the summer. Nitrate extinction at 2.7 1/Mm is lowest in the summer and in the spring it peaks at 5.2 1/Mm and in the winter 4.0 1/Mm. The seasonal variation of sulfates, organics, and nitrates are driven by seasonal changes in meteorology and photochemistry. For sulfates and organics this leads to higher concentrations during the summer. This coupled with the fact that RH is highest in the summer leads to high specific scattering for sulfate aerosols. Nitrates, on the other hand, are volatile. The lower temperatures during the winter and spring lead to higher concentrations of nitrates. Sulfate extinction comprises the largest fraction of aerosol extinction accounting for 77.1% annually and varies from a high during the summer of 85.7% down to 67.9% in the winter. The next highest contributor on an annual basis is organics (10.6%), followed by nitrate (4.6%), light-absorbing carbon (4.2%), and soil and coarse particles (3.5%).

Boundary Waters. The Boundary Waters Canoe Area represents this region in northern Minnesota, in the Superior National Forest. Annual average extinction here is about 44.6 1/Mm of which 78% is due to the ambient aerosol. The seasonal variation is significant, and ranges from a high in the winter of 52.9 1/Mm to as low as 36.3 1/Mm in the spring. Sulfate contributes the most to extinction (54.1%), the next largest contributor is organics (17%) followed by nitrate (16.3%), soil and coarse particles (7.2%) and light-absorbing carbon (5.4%).

**Table 3.2** Seasonal and annual averages of reconstructed total light-extinction coefficient (including Rayleigh) for the 21 regions in the IMPROVE Network. Also shown are the light scatterings resulting from fine and coarse aerosols, light absorption for carbonaceous aerosol, percentage of total extinction resulting from aerosol extinction and the average regional relative humidity.

Season	Total Reconstructed Extinction (1/Mm)	Fine Reconstructed Scattering (1/Mm)	Coarse Scattering (1/Mm)	Absorption (1/Mm)	Percent Aerosol	Relative Humidity (%)
<b>Alaska</b>						
ANNUAL	20.0	7.0	2.0	1.0	50	65
Spring	20.0	6.9	2.2	0.9	50	56
Summer	22.3	9.2	2.1	1.0	55	64
Autumn	18.7	5.5	2.1	1.1	47	72
Winter	17.9	5.5	1.5	0.9	44	68
<b>Appalachian</b>						
ANNUAL	98.5	81.6	3.1	3.7	90	71
Spring	78.8	61.6	3.6	3.6	87	64
Summer	169.0	151.5	3.7	3.8	94	79
Autumn	88.9	71.9	2.8	4.1	89	69
Winter	61.0	45.4	2.3	3.3	84	71
<b>Boundary Waters</b>						
ANNUAL	44.6	30.3	2.5	1.9	78	71
Spring	36.3	22.4	2.4	1.4	72	61
Summer	48.0	32.8	2.9	2.3	79	69
Autumn	43.8	28.7	3.0	2.2	77	77
Winter	52.9	39.2	1.9	1.8	81	79
<b>Cascade Mountains</b>						
ANNUAL	41.5	26.6	2.2	2.7	76	77
Spring	37.6	23.7	1.9	2.0	73	76
Summer	50.9	34.3	3.1	3.6	80	71
Autumn	41.4	25.9	2.2	3.3	76	78
Winter	26.6	13.4	1.5	1.6	62	85
<b>Central Rocky Mountains</b>						
ANNUAL	23.8	10.0	2.6	1.3	58	56
Spring	27.7	13.4	3.1	1.2	64	64
Summer	26.2	11.7	3.0	1.5	62	46
Autumn	23.5	9.7	2.4	1.4	57	55
Winter	18.7	6.1	1.7	0.9	46	60
<b>Colorado Plateau</b>						
ANNUAL	25.6	10.7	3.2	1.7	61	48
Spring	26.2	10.3	4.2	1.6	62	45
Summer	28.3	12.8	3.7	1.8	65	41
Autumn	24.8	10.3	2.7	1.8	60	46
Winter	22.0	8.5	2.1	1.4	55	59
<b>Great Basin</b>						
ANNUAL	22.9	8.1	3.4	1.4	56	50
Spring	22.1	8.1	2.8	1.2	55	53
Summer	27.4	10.6	5.2	1.6	63	39
Autumn	22.0	7.7	3.0	1.3	55	47
Winter	17.5	4.6	1.8	1.2	43	59

*Table 3.2 Continued.*

Season	Total Reconstructed Extinction (1/Mm)	Fine Reconstructed Scattering (1/Mm)	Coarse Scattering (1/Mm)	Absorption (1/Mm)	Percent Aerosol	Relative Humidity (%)
<b>Mid Atlantic</b>						
ANNUAL	103.0	79.6	8.3	5.1	90	71
Spring	110.1	83.9	12.0	4.2	91	73
Summer	146.2	123.0	8.6	4.7	93	77
Autumn	84.6	63.4	5.3	5.9	88	69
Winter	79.5	57.0	6.7	5.8	87	67
<b>Mid South</b>						
ANNUAL	120.5	101.9	3.8	4.8	92	73
Spring	90.9	72.4	4.0	4.4	89	66
Summer	200.8	180.9	5.3	4.6	95	80
Autumn	124.3	105.1	3.5	5.7	92	74
Winter	79.6	63.0	2.3	4.3	87	71
<b>Northeast</b>						
ANNUAL	55.4	40.4	2.5	2.5	82	72
Spring	44.9	30.1	2.7	2.1	78	66
Summer	77.7	62.4	2.5	2.8	87	73
Autumn	51.7	36.6	2.5	2.5	81	76
Winter	47.1	32.3	2.2	2.6	79	73
<b>Northern Great Plains</b>						
ANNUAL	36.7	21.5	3.7	1.4	73	63
Spring	40.2	24.9	4.0	1.3	75	62
Summer	38.1	22.5	4.2	1.5	74	61
Autumn	34.8	19.3	3.9	1.6	71	60
Winter	33.6	19.5	2.9	1.2	70	69
<b>Northern Rocky Mountains</b>						
ANNUAL	41.8	23.9	4.3	3.6	76	76
Spring	42.2	25.7	3.3	3.1	76	76
Summer	41.7	21.3	7.4	3.0	76	69
Autumn	45.9	26.6	4.2	5.1	78	79
Winter	37.3	22.0	2.2	3.1	73	83
<b>Pacific Coastal Mountains</b>						
ANNUAL	47.3	31.2	4.2	1.9	79	72
Spring	45.9	29.9	4.4	1.7	78	72
Summer	53.9	38.2	4.5	1.2	81	71
Autumn	44.7	27.4	4.7	2.6	78	70
Winter	36.1	20.8	3.4	2.0	72	73
<b>Sierra-Humboldt</b>						
ANNUAL	23.8	9.8	2.2	1.8	58	61
Spring	22.8	9.1	2.3	1.4	56	63
Summer	32.7	17.3	2.9	2.5	69	69
Autumn	23.5	9.4	1.9	2.1	57	51
Winter	16.6	3.8	1.6	1.1	40	62
<b>Sierra Nevada</b>						
ANNUAL	45.1	26.0	5.4	3.8	78	51
Spring	42.6	24.1	5.2	3.3	77	59
Summer	51.1	28.4	7.8	4.9	80	42
Autumn	46.5	25.6	6.2	4.7	78	45
Winter	37.5	22.8	2.4	2.3	73	56

*Table 3.2 Continued.*

Season	Total Reconstructed Extinction (1/Mm)	Fine Reconstructed Scattering (1/Mm)	Coarse Scattering (1/Mm)	Absorption (1/Mm)	Percent Aerosol	Relative Humidity (%)
<b>Sonoran Desert</b>						
ANNUAL	29.4	12.9	4.7	1.8	66	42
Spring	28.6	10.9	6.2	1.5	65	35
Summer	32.9	15.8	5.5	1.6	70	41
Autumn	30.0	13.6	4.2	2.2	67	40
Winter	25.1	10.4	2.9	1.8	60	52
<b>Southeast</b>						
ANNUAL	109.2	87.7	6.5	5.1	91	75
Spring	103.5	81.6	6.8	5.0	90	70
Summer	124.8	103.0	8.3	3.5	92	77
Autumn	119.0	97.9	5.8	5.3	92	78
Winter	87.1	65.6	5.2	6.3	89	75
<b>Southern California</b>						
ANNUAL	52.8	34.4	4.7	3.7	81	48
Spring	68.9	49.7	5.1	4.0	85	54
Summer	57.2	35.8	6.3	5.0	83	44
Autumn	39.1	21.4	4.6	3.1	74	42
Winter	36.0	21.6	2.2	2.2	72	52
<b>Wasatch</b>						
ANNUAL	33.9	16.6	4.0	3.3	70	55
Spring	31.0	14.5	3.7	2.8	68	54
Summer	36.7	17.1	5.4	4.2	73	41
Autumn	31.1	14.2	3.6	3.3	68	54
Winter	38.0	22.1	3.1	2.8	74	70
<b>Washington, D.C.</b>						
ANNUAL	115.8	90.6	3.7	11.5	91	65
Spring	104.3	80.4	3.8	10.1	90	62
Summer	147.5	123.4	3.5	10.7	93	68
Autumn	116.3	89.0	4.4	12.9	91	68
Winter	97.0	71.3	3.2	12.6	90	62
<b>West Texas</b>						
ANNUAL	36.1	18.7	5.7	1.7	72	45
Spring	38.5	18.2	8.4	1.9	74	37
Summer	39.6	22.0	6.3	1.3	75	48
Autumn	37.1	21.4	3.8	1.8	73	49
Winter	28.8	13.0	4.1	1.6	65	47

**Table 3.3** Seasonal and annual averages of reconstructed aerosol light-extinction coefficient for the 21 regions in the IMPROVE Network. Also shown are light extinctions resulting from sulfate, nitrate, organic carbon, light-absorbing carbon, and soil and coarse particles.

Season	Aerosol Reconstructed Extinction (1/Mm)	Sulfate (1/Mm)	Nitrate (1/Mm)	Organics (1/Mm)	Light-Absorbing Carbon (1/Mm)	Soil and Coarse (1/Mm)
<b>Alaska</b>						
ANNUAL	10.0	3.9	0.4	2.7	1.0	2.0
Spring	10.0	4.7	0.4	1.8	0.9	2.2
Summer	12.3	3.5	0.3	5.5	1.0	2.1
Autumn	8.7	3.2	0.4	1.9	1.1	2.1
Winter	7.9	3.5	0.8	1.2	0.9	1.5
<b>Appalachian</b>						
ANNUAL	88.5	68.2	4.0	9.4	3.7	3.1
Spring	68.8	47.9	5.2	8.5	3.6	3.6
Summer	159.0	136.3	2.7	12.5	3.8	3.7
Autumn	78.9	58.9	3.7	9.3	4.1	2.8
Winter	51.0	34.6	4.0	6.8	3.3	2.3
<b>Boundary Waters</b>						
ANNUAL	34.6	18.7	5.6	5.9	1.9	2.5
Spring	26.3	14.4	3.8	4.2	1.4	2.4
Summer	38.0	20.3	1.2	11.3	2.3	2.9
Autumn	33.8	17.3	5.3	6.1	2.2	3.0
Winter	42.9	22.4	12.8	4.0	1.8	1.9
<b>Cascade Mountains</b>						
ANNUAL	31.5	16.6	3.3	6.7	2.7	2.2
Spring	27.6	16.0	3.1	4.6	2.0	1.9
Summer	40.9	21.3	3.3	9.7	3.6	3.1
Autumn	31.4	14.3	3.1	8.5	3.3	2.2
Winter	16.6	6.8	3.2	3.4	1.6	1.5
<b>Central Rocky Mountains</b>						
ANNUAL	13.8	5.2	1.0	3.9	1.3	2.6
Spring	17.7	8.0	2.0	3.5	1.2	3.1
Summer	16.2	5.2	0.7	5.8	1.5	3.0
Autumn	13.5	5.1	0.8	3.9	1.4	2.4
Winter	8.7	3.3	0.8	2.0	0.9	1.7
<b>Colorado Plateau</b>						
ANNUAL	15.6	5.8	1.1	3.8	1.7	3.2
Spring	16.2	5.0	1.4	3.9	1.6	4.2
Summer	18.3	6.9	0.9	4.9	1.8	3.7
Autumn	14.8	5.9	0.7	3.6	1.8	2.7
Winter	12.0	4.6	1.5	2.5	1.4	2.1
<b>Great Basin</b>						
ANNUAL	12.9	3.2	0.7	4.2	1.4	3.4
Spring	12.1	3.7	0.9	3.4	1.2	2.8
Summer	17.4	3.6	0.7	6.4	1.6	5.2
Autumn	12.0	3.3	0.6	3.8	1.3	3.0
Winter	7.5	1.5	0.6	2.4	1.2	1.8

*Table 3.3 Continued.*

Season	Aerosol Reconstructed Extinction (1/Mm)	Sulfate (1/Mm)	Nitrate (1/Mm)	Organics (1/Mm)	Light-Absorbing Carbon (1/Mm)	Soil and Coarse (1/Mm)
<b>Mid Atlantic</b>						
ANNUAL	93.0	61.4	8.6	9.6	5.1	8.3
Spring	100.1	65.9	10.9	7.1	4.2	12.0
Summer	136.2	105.1	5.8	12.1	4.7	8.6
Autumn	74.6	47.2	6.6	9.5	5.9	5.3
Winter	69.5	37.8	9.3	9.9	5.8	6.7
<b>Mid South</b>						
ANNUAL	110.5	81.6	8.8	11.4	4.8	3.8
Spring	80.9	53.1	8.6	10.7	4.4	4.0
Summer	190.8	161.5	5.3	14.1	4.6	5.3
Autumn	114.3	85.3	7.5	12.4	5.7	3.5
Winter	69.6	42.3	12.4	8.3	4.3	2.3
<b>Northeast</b>						
ANNUAL	45.4	30.9	3.3	6.2	2.5	2.5
Spring	34.9	22.7	2.9	4.6	2.1	2.7
Summer	67.7	50.7	2.3	9.5	2.8	2.5
Autumn	41.7	27.6	3.4	5.6	2.5	2.5
Winter	37.1	22.4	4.7	5.2	2.6	2.2
<b>Northern Great Plains</b>						
ANNUAL	26.7	13.0	4.0	4.5	1.4	3.7
Spring	30.2	15.5	5.8	3.6	1.3	4.0
Summer	28.1	14.5	1.1	6.8	1.5	4.2
Autumn	24.8	11.2	3.1	4.9	1.6	3.9
Winter	23.6	10.8	6.1	2.7	1.2	2.9
<b>Northern Rocky Mountains</b>						
ANNUAL	31.8	11.1	2.8	10.1	3.6	4.3
Spring	32.2	14.0	2.8	9.0	3.1	3.3
Summer	31.7	9.3	1.4	10.6	3.0	7.4
Autumn	35.9	10.3	2.4	13.9	5.1	4.2
Winter	27.3	10.4	4.8	6.8	3.1	2.2
<b>Pacific Coastal Mountains</b>						
ANNUAL	37.3	17.9	8.0	5.3	1.9	4.2
Spring	35.9	17.5	7.7	4.7	1.7	4.4
Summer	43.9	26.9	7.0	4.3	1.2	4.5
Autumn	34.7	14.2	6.1	7.1	2.6	4.7
Winter	26.1	7.4	8.4	4.9	2.0	3.4
<b>Sierra-Humboldt</b>						
ANNUAL	13.8	3.9	1.0	5.0	1.8	2.2
Spring	12.8	4.3	1.2	3.6	1.4	2.3
Summer	22.7	7.9	1.7	7.8	2.5	2.9
Autumn	13.5	2.6	0.7	6.1	2.1	1.9
Winter	6.6	1.4	0.6	1.9	1.1	1.6
<b>Sierra Nevada</b>						
ANNUAL	35.1	8.6	6.3	11.1	3.8	5.4
Spring	32.6	9.2	6.5	8.4	3.3	5.2
Summer	41.1	9.4	2.6	16.4	4.9	7.8
Autumn	36.5	6.3	5.0	14.2	4.7	6.2
Winter	27.5	4.8	12.1	5.9	2.3	2.4

*Table 3.3 Continued.*

Season	Aerosol Reconstructed Extinction (1/Mm)	Sulfate (1/Mm)	Nitrate (1/Mm)	Organics (1/Mm)	Light-Absorbing Carbon (1/Mm)	Soil and Coarse (1/Mm)
<b>Sonoran Desert</b>						
ANNUAL	19.4	7.3	1.1	4.4	1.8	4.7
Spring	18.6	5.1	1.2	4.6	1.5	6.2
Summer	22.9	10.4	1.0	4.5	1.6	5.5
Autumn	20.0	7.8	0.8	5.0	2.2	4.2
Winter	15.1	5.4	1.5	3.5	1.8	2.9
<b>Southeast</b>						
ANNUAL	99.2	70.8	5.4	11.4	5.1	6.5
Spring	93.5	65.1	5.6	10.9	5.0	6.8
Summer	114.8	87.6	4.5	10.8	3.5	8.3
Autumn	109.0	81.9	4.8	11.2	5.3	5.8
Winter	77.1	47.2	5.7	12.7	6.3	5.2
<b>Southern California</b>						
ANNUAL	42.8	9.7	16.5	8.1	3.7	4.7
Spring	58.9	11.9	28.9	9.0	4.0	5.1
Summer	47.2	11.5	12.2	12.1	5.0	6.3
Autumn	29.1	6.4	8.8	6.3	3.1	4.6
Winter	26.0	3.9	13.7	4.0	2.2	2.2
<b>Wasatch</b>						
ANNUAL	23.9	6.6	3.7	6.3	3.3	4.0
Spring	21.0	6.2	3.0	5.2	2.8	3.7
Summer	26.7	5.6	1.4	10.1	4.2	5.4
Autumn	21.1	6.6	2.2	5.4	3.3	3.6
Winter	28.0	7.3	10.8	4.0	2.8	3.1
<b>Washington, D.C.</b>						
ANNUAL	105.8	61.7	13.5	15.3	11.5	3.7
Spring	94.3	55.0	13.7	11.8	10.1	3.8
Summer	137.5	100.2	6.8	16.4	10.7	3.5
Autumn	106.3	57.7	15.4	16.0	12.9	4.4
Winter	87.0	36.3	17.5	17.4	12.6	3.2
<b>West Texas</b>						
ANNUAL	26.1	12.5	1.3	4.9	1.7	5.7
Spring	28.5	10.0	1.4	6.8	1.9	8.4
Summer	29.6	15.5	1.5	5.0	1.3	6.3
Autumn	27.1	16.1	0.8	4.5	1.8	3.8
Winter	18.8	8.6	1.3	3.1	1.6	4.1

**Table 3.4** Seasonal and annual averages of percentage contributions to the reconstructed aerosol light-extinction coefficient (light-extinction budget) for the 21 regions in the IMPROVE Network for sulfate, nitrate, organic carbon, light-absorbing carbon, and soil and coarse particles.

Season	Sulfate	Nitrate	Organics	Light-Absorbing Carbon	Soil and Coarse
<b>Alaska</b>					
ANNUAL	38.9	4.5	27.0	9.7	19.9
Spring	46.8	3.8	18.2	9.1	22.1
Summer	28.2	2.2	44.4	8.1	17.0
Autumn	37.4	4.4	21.9	12.1	24.2
Winter	43.8	9.6	15.8	11.3	19.5
<b>Appalachian</b>					
ANNUAL	77.1	4.6	10.6	4.2	3.5
Spring	69.6	7.5	12.3	5.3	5.2
Summer	85.7	1.7	7.9	2.4	2.3
Autumn	74.7	4.7	11.8	5.2	3.6
Winter	67.9	7.8	13.4	6.5	4.5
<b>Boundary Waters</b>					
ANNUAL	54.1	16.3	17.0	5.4	7.2
Spring	54.9	14.4	16.0	5.5	9.1
Summer	53.6	3.1	29.8	5.9	7.6
Autumn	51.2	15.6	18.0	6.4	8.8
Winter	52.3	29.9	9.3	4.1	4.3
<b>Cascade Mountains</b>					
ANNUAL	52.8	10.5	21.1	8.4	7.1
Spring	58.0	11.0	16.8	7.3	6.8
Summer	52.1	8.0	23.6	8.7	7.6
Autumn	45.4	9.9	27.1	10.5	7.1
Winter	41.1	19.2	20.6	9.8	9.3
<b>Central Rocky Mountains</b>					
ANNUAL	37.3	7.1	27.8	9.1	18.7
Spring	44.9	11.3	19.5	6.8	17.6
Summer	32.1	4.6	35.6	9.1	18.6
Autumn	37.6	5.6	28.7	10.4	17.6
Winter	37.8	9.5	22.9	10.5	19.3
<b>Colorado Plateau</b>					
ANNUAL	37.2	7.2	24.2	10.7	20.7
Spring	30.9	8.8	24.3	9.9	26.2
Summer	37.9	5.0	27.0	10.0	20.1
Autumn	40.2	5.0	24.6	11.9	18.3
Winter	37.8	12.4	20.5	11.8	17.5
<b>Great Basin</b>					
ANNUAL	24.8	5.6	32.6	10.7	26.3
Spring	31.0	7.7	28.0	9.7	23.6
Summer	20.7	3.9	36.6	9.1	29.7
Autumn	27.8	5.2	31.3	11.1	24.6
Winter	20.5	7.9	32.2	16.1	23.3

Table 3.4 Continued.

Season	Sulfate	Nitrate	Organics	Light-Absorbing Carbon	Soil and Coarse
<b>Mid Atlantic</b>					
ANNUAL	66.1	9.2	10.3	5.5	8.9
Spring	65.8	10.9	7.1	4.2	12.0
Summer	77.1	4.3	8.9	3.4	6.3
Autumn	63.3	8.9	12.7	7.9	7.2
Winter	54.3	13.4	14.2	8.4	9.6
<b>Mid South</b>					
ANNUAL	73.9	8.0	10.3	4.3	3.5
Spring	65.7	10.6	13.3	5.5	5.0
Summer	84.7	2.8	7.4	2.4	2.8
Autumn	74.6	6.5	10.8	5.0	3.1
Winter	60.7	17.8	11.9	6.2	3.4
<b>Northeast</b>					
ANNUAL	67.9	7.4	13.7	5.5	5.5
Spring	65.0	8.3	13.1	6.0	7.7
Summer	74.9	3.3	14.0	4.1	3.6
Autumn	66.1	8.2	13.5	6.1	6.1
Winter	60.4	12.6	14.1	7.0	6.0
<b>Northern Great Plains</b>					
ANNUAL	48.8	14.9	17.0	5.3	14.0
Spring	51.4	19.3	12.0	4.2	13.2
Summer	51.7	3.8	24.3	5.4	14.7
Autumn	45.2	12.7	19.8	6.6	15.7
Winter	45.7	25.7	11.3	5.1	12.1
<b>Northern Rocky Mountains</b>					
ANNUAL	34.8	8.7	31.7	11.3	13.4
Spring	43.6	8.6	27.9	9.8	10.2
Summer	29.2	4.5	33.5	9.5	23.3
Autumn	28.7	6.7	38.8	14.3	11.6
Winter	38.2	17.5	24.9	11.4	8.0
<b>Pacific Coastal Mountains</b>					
ANNUAL	47.9	21.5	14.2	5.0	11.4
Spring	48.7	21.5	13.1	4.6	12.1
Summer	61.3	16.0	9.8	2.7	10.3
Autumn	41.0	17.6	20.4	7.4	13.6
Winter	28.3	32.2	18.9	7.6	12.8
<b>Sierra-Humbolt</b>					
ANNUAL	27.8	7.1	35.9	13.2	15.9
Spring	33.4	9.5	27.9	10.9	18.3
Summer	34.8	7.3	34.2	11.0	12.6
Autumn	19.6	5.2	45.3	15.9	14.0
Winter	21.4	8.5	28.6	17.1	24.5
<b>Sierra Nevada</b>					
ANNUAL	24.4	17.8	31.6	10.7	15.4
Spring	28.3	19.8	25.8	10.1	16.0
Summer	23.0	6.3	39.8	11.8	19.0
Autumn	17.4	13.7	39.0	12.8	17.1
Winter	17.4	44.0	21.5	8.4	8.7

**Table 3.4 Continued.**

Season	Sulfate	Nitrate	Organics	Light-Absorbing Carbon	Soil and Coarse
<b>Sonoran Desert</b>					
ANNUAL	37.9	5.9	22.7	9.1	24.4
Spring	27.2	6.7	24.6	8.3	33.3
Summer	45.3	4.5	19.5	6.8	23.9
Autumn	39.2	4.0	25.1	10.8	20.9
Winter	35.5	10.0	23.3	12.1	19.0
<b>Southeast</b>					
ANNUAL	71.4	5.4	11.5	5.1	6.6
Spring	69.6	6.0	11.7	5.4	7.3
Summer	76.3	4.0	9.4	3.0	7.3
Autumn	75.1	4.4	10.3	4.9	5.3
Winter	61.2	7.4	16.5	8.2	6.7
<b>Southern California</b>					
ANNUAL	22.7	38.6	19.0	8.6	11.1
Spring	20.2	49.0	15.3	6.8	8.7
Summer	24.4	25.8	25.7	10.7	13.4
Autumn	21.8	30.1	21.7	10.7	15.8
Winter	15.1	52.9	15.2	8.5	8.4
<b>Wasatch</b>					
ANNUAL	27.8	15.7	26.2	13.7	16.7
Spring	29.7	14.4	24.8	13.2	17.8
Summer	20.8	5.1	38.0	15.7	20.3
Autumn	31.1	10.5	25.6	15.8	16.9
Winter	26.1	38.5	14.4	9.8	11.1
<b>Washington, D.C.</b>					
ANNUAL	58.4	12.7	14.5	10.9	3.5
Spring	58.4	14.5	12.5	10.7	4.0
Summer	72.9	5.0	11.9	7.8	2.5
Autumn	54.2	14.5	15.0	12.1	4.1
Winter	41.7	20.1	20.0	14.4	3.7
<b>West Texas</b>					
ANNUAL	47.8	5.0	18.8	6.4	22.0
Spring	35.1	5.0	23.9	6.7	29.4
Summer	52.3	5.1	16.9	4.3	21.4
Autumn	59.5	3.1	16.6	6.8	14.0
Winter	45.6	7.1	16.7	8.6	22.0

Cascade Mountains. Three sites, Mount Rainier National Park southeast of Seattle, Snoqualmie Pass to the northeast of Seattle, and Three Sisters Wilderness Area in Oregon now represent this region. The average annual extinction for this region is 41.5 1/Mm, of which 76% is due to aerosols. The seasonality is significant and ranges from a high in the summer of 50.9 1/Mm then drops to a low in the winter of 26.6 1/Mm. The seasonality is driven primarily by sulfate. Sulfate extinction ranges from a summer high of 21.3 1/Mm then drops to 6.8 1/Mm in the summer. Organics also show significant variance between seasons with an annual average value of 6.7 1/Mm and a minimum of 3.4 1/Mm in the winter to as high as 9.7 1/Mm in the summer. The largest contributor to aerosol extinction is sulfate (52.8%), followed by organics (21.1%), nitrate (10.5%), light-absorbing carbon (8.4%), and coarse extinction (7.1%).

Central Rocky Mountains. The measurements in this region were made at six locations in the mountainous Class I areas of Colorado and Wyoming, including the Bridger, Mount Zirkel, and Weminuche Wilderness Areas, Rocky Mountain and Yellowstone National Parks, and Great Sand Dunes National Monument. Monitoring began in the summer of 1994 at Mount Zirkel, and the other five sites have operated since March of 1988. The six sites show an annual average total extinction for the three-year period of 23.8 1/Mm, of which 58% is due to aerosol extinction. The seasonal variation is relatively small and has a maximum in the spring and summer of 27.7 and 26.2 1/Mm, respectively, and decreases to 18.7 1/Mm during the winter. Extinction due to organics, and absorption is highest in the summer and least in the winter. Organic extinction peaks at 5.8 1/Mm in the summer and drops in the winter to 2.0 1/Mm. Absorption ranges for 1.5 1/Mm in the summer and drops to 0.9 1/Mm in the winter. Sulfates (37.3%) contribute the most to extinction annually followed by organics (27.8%), soil and coarse (18.7%), light-absorbing carbon (9.1%), and nitrate is the smallest contributor (7.1%).

Colorado Plateau. This region in the Four Corners' states of the Southwest is the most intensively monitored in the IMPROVE Network. There are six sites, most of them within the so-called Golden Circle of National Parks: Bandelier, Bryce Canyon, Canyonlands, Grand Canyon, Mesa Verde, and Petrified Forest. The three-year annual average for total extinction is relatively low at 25.6 1/Mm, 61% of which is aerosol extinction. There is a very slight variance between seasons of total extinction ranging from 22 1/Mm in the winter to as high as 28.3 1/Mm during the summer. Sulfate extinction reaches its maximum at 6.9 1/Mm in summer and is lowest in winter at 4.6 1/Mm. Nitrate extinction is typically high during the winter at 1.5 1/Mm and lowest during the autumn at 0.7 1/Mm. The largest contribution to annual aerosol extinction is sulfate (37.2%) followed by organics (24.2%), soil and coarse particles (20.7%), light-absorbing carbon (10.7%), and nitrate (7.2%).

Great Basin. Two sites represent the Great Basin of Nevada, Jarbidge Wilderness Area in northeastern Nevada and Great Basin National Park. The annual average extinction during the three-year period for this region is quite low at 22.9 1/Mm, with 56% from aerosol extinction, the only region with less extinction is Alaska. A seasonal variation exists between 27.4 1/Mm during the summer and 17.5 1/Mm during the winter. On an annual basis the largest contributor to extinction is organics (32.6%) followed by soil and coarse particles (26.3%), and sulfate (24.8%). This region is unique in that sulfate is the third largest contributor to extinction. This holds for two out of the four seasons (summer and winter).

Mid Atlantic. This region, represented by the Edwin B. Forsythe National Wildlife Refuge, just west of Atlantic City, New Jersey, has an average annual reconstructed extinction of 103 1/Mm. There is a significant seasonality, with extinction moving from a high during the summer of 146.2 1/Mm, to 79.5 1/Mm in the winter. Sulfate extinction is 105.1 1/Mm in the summer and 37.8 1/Mm in the winter, and is responsible for most of the seasonality. Sulfates are responsible for about two thirds (66.1%) of the aerosol extinction, followed by organics (10.3%), nitrate (9.2%), soil and coarse particles (8.9%), and light-absorbing carbon (5.5%).

Mid South. Three sites represent this region: Sipsey Wilderness Area in northern Mississippi, Upper Buffalo Wilderness Area in northern Arkansas, and Mammoth Cave National Park in Kentucky. This region has the highest levels of reconstructed extinction. The average annual

reconstructed extinction is 120.5 1/Mm with a significant seasonal variation between the summer high of 200.8 1/Mm and the winter low of 79.6 1/Mm. Sulfate dominates the aerosol extinction and is responsible for much of the seasonality observed. Sulfate extinction is highest in the summer at 161.5 1/Mm and lowest in the winter at 42.3 1/Mm. Organics, and light-absorbing carbon all have seasonal trends that peak in the summer for organics and autumn for absorption but are lowest in the winter for organics and spring for absorption. On an annual average, sulfate contributes 73.9% of the aerosol extinction peaking in the summer (84.7%) and is least in the winter (60.7%). The next largest contributor annually is organics (10.3%), followed by nitrate (8%), light-absorbing carbon (4.3%), and soil and coarse particles (3.5%).

Northeast. The northeastern United States is represented by measurements at three sites: Acadia National Park and Moosehorn National Wildlife Refuge in Maine, and Lye Brook Wilderness Area in Vermont. The average annual extinction during the three-year period for the Northeast is 55.4 1/Mm of which aerosol extinction accounts for 82%. There is a significant seasonal variation from the spring minimum of 44.9 1/Mm and the highest during the summer at 77.7 1/Mm. Sulfates and organics are responsible for most of the seasonal variation with sulfates varying from 22.4 1/Mm to 50.7 1/Mm between winter and summer and organics varying between 4.6 1/Mm in the spring to 9.5 1/Mm in the summer. Nitrate extinction obtains its maximum during the winter at 4.7 1/Mm and its minimum at 2.3 1/Mm during the summer. The largest contributor to extinction is from sulfates at 67.9% annually. The next highest contributor is organics (13.7%), followed by nitrate (7.4%), and soil and coarse particles and light-absorbing carbon (both at 5.5%).

Northern Great Plains. Aerosol measurements were made at one site in this region, Badlands National Park in South Dakota, where reconstructed light extinction averaged 36.7 1/Mm. Unlike most other regions, extinction was highest in spring and lowest in winter. This seasonality is driven primarily by sulfate and nitrate extinction. Sulfate extinction reaches a maximum of 15.5 1/Mm in the spring and a minimum of 10.8 1/Mm in the winter. Nitrate extinction in the winter, 6.1 1/Mm, is almost six times its summer extinction of 1.1 1/Mm. The main contributor to annual extinction is sulfate, which accounts for 48.8% of the extinction. The next highest contributor is organics (17%), followed by nitrate (14.9%), soil and coarse particles (14%) and light-absorbing carbon (5.3%).

Northern Rocky Mountains. This region is represented by one site, Glacier National Park, which is close to the Canada border. The reconstructed light extinction coefficient is 41.8 1/Mm for an annual average of 76% due to aerosols. There is modest seasonality ranging between 45.9 1/Mm in the autumn down to 37.3 1/Mm during the winter. The seasonality is driven by sulfate and nitrate extinction. Sulfate and nitrate extinctions peak at 14 1/Mm and 4.8 1/Mm, during the spring and winter, respectively. The largest contributor to aerosol extinction is sulfate (34.8%) followed by organics (31.7%), soil and coarse particles (13.4%), light-absorbing carbon (11.3%), and nitrate (8.7%).

Pacific Coastal Mountains. This region includes three Class I areas near the coast of northern California: Pinnacles National Monument, Point Reyes National Seashore, and Redwood National Park. The average annual extinction during the three-year period for this area is 47.3 1/Mm with 79% due to aerosol extinction. The annual variance is moderate and ranges between 53.9 1/Mm during the summer and 36.1 1/Mm during the winter. Sulfate extinction reaches its maximum in the summer at 26.9 1/Mm when nitrate extinction is near its minimum at 7 1/Mm. When nitrate

extinction obtains its maximum of 8.4 1/Mm during the winter, sulfate extinction is at its minimum of 7.4 1/Mm. Organic extinction and absorption obtain their maxima in the autumn of 7.1 1/Mm and 2.6 1/Mm, respectively. On an annual basis, the largest contributor to aerosol extinction is sulfate (47.9%), followed by nitrate (21.5%), organics (14.2%), soil and coarse (11.4%), and light-absorbing carbon (5.0%). The contribution from sulfate shows considerable variation ranging from a high in the summer of 61.3% to 28.3% in the winter when its contribution is eclipsed by nitrate (32.2)%.

Sierra-Humboldt. The region in the Sierra Nevada and Humboldt Mountain Ranges was measured at Crater Lake National Park in Oregon and Lassen Volcanic National Park in northern California. For this region, total reconstructed light extinction averaged 23.8 1/Mm with maximum extinction in summer (32.7 1/Mm) and minimum extinction in winter (16.6 1/Mm). The seasonality is primarily due to variations in sulfate and organic extinctions and absorption. Organics contribute the most to extinction (35.9%), followed by sulfate (27.8%), soil and coarse particles (15.9%), light-absorbing carbon (13.2%), and nitrate (7.1%).

Sierra Nevada. Aerosols in the Sierra Nevada region are monitored at two sites: Yosemite and Sequoia National Parks. The average reconstructed light extinction is 45.1 1/Mm with a seasonal component that has a winter minimum of 37.5 1/Mm and a summer maximum of 51.1 1/Mm. The seasonality is driven primarily by organics and absorption with both species peaking during the summer at 16.4 1/Mm and 4.9 1/Mm, then dropping to their minimum at 5.9 1/Mm and 2.3 1/Mm during the winter. Sulfate, to a lesser extent, is responsible for the seasonality, its maximum occurs in the summer at 9.4 1/Mm and obtains its seasonal low in the winter at 4.8 1/Mm. Nitrate shows a very strong seasonal component with a winter high of 12.1 1/Mm to a summer low of 2.6 1/Mm. On an annual average, organics contribute the most to aerosol extinction (31.6%), followed by sulfate (24.4%), nitrate (17.8%), then soil and coarse particles (15.4%), and finally light-absorbing carbon (10.7%).

Sonoran Desert. This region in southeastern Arizona was measured at two sites: Chiricahua and Tonto National Monuments. The three-year average reconstructed extinction is 29.4 1/Mm and varies from a summer high of 32.9 1/Mm to a winter low of 25.1 1/Mm. The seasonality is due to changes in extinction from sulfate, organics, and absorption. Organics and absorption obtain their seasonal maxima of 5.0 1/Mm and 2.2 1/Mm during the autumn. Sulfate obtains its maximum extinction during the summer at 10.4 1/Mm and its minimum of 5.4 1/Mm in the winter. The largest contributor to extinction is sulfate (37.9%) followed by soil and coarse particles (24.4%), organics (22.7%), light-absorbing carbon (9.1%), and nitrate (5.9%).

Southeast. This region consists of three sites, Chassahowitzka National Wildlife Refuge north of Tampa, Florida, Okefenokee National Wildlife Refuge on the Georgia-Florida border, and Cape Romain National Wildlife Refuge on the South Carolina coast. The annual total extinction for this region is 109.2 1/Mm, 91% is due to aerosol extinction. A seasonal variance exists here, with summer having the most extinction of 124.8 1/Mm and winter the least at 87.1 1/Mm. The largest contributor to aerosol extinction is from sulfates (71.4%), followed by organics (11.7%), soil and coarse particles (6.6%), nitrate (5.4%), and light-absorbing carbon (5.1%).

Southern California. Measurements in this region were made in San Gorgonio Wilderness Area, east of the Los Angeles metropolitan area. Total reconstructed light extinction averaged over the three-year period was 52.8 1/Mm and varied from a seasonal high of 68.9 1/Mm in the spring to as little as 36.0 1/Mm in the winter. The seasonality is driven primarily by nitrates and to a lesser extent sulfate, organics, and absorption. This region is unique in that nitrates are by far the largest contributor to annual extinction (38.6%), followed by sulfate (22.7%), organics (19.0%), soil and coarse particles (11.1%), and light-absorbing carbon (8.6%).

Wasatch. This region is represented by the Lone Peak Wilderness Area northeast of Provo, Utah. It has an annual average extinction of 33.9 1/Mm. This area is somewhat unique in that it obtains the maximum light extinction during the winter of 38.0 1/Mm and the least during spring and autumn at 31.0 1/Mm and 31.1 1/Mm, respectively. This seasonality is driven by sulfate and nitrate extinction, which obtain their maximums during the winter of 7.3 1/Mm and 10.8 1/Mm, respectively, while organics and absorption peak in the summer at 10.1 1/Mm and 4.2 1/Mm, respectively. On average sulfate (27.8%) and organics (26.2%) contribute almost equally to aerosol extinction followed by soil and coarse particles (16.7%), nitrate (15.7%), and light-absorbing carbon (13.7%).

West Texas. Total light extinction reconstructed from the aerosol measurements at Big Bend and Guadalupe Mountains National Parks averaged 36.1 1/Mm over the three-year period. Seasonality is evident with the highest extinction in the summer (39.6 1/Mm) and the least during the winter (28.8 1/Mm). The seasonality is primarily due to sulfate, which is the largest contributor to aerosol extinction (47.8%), soil and coarse particles (22%), followed by organics (18.8%), light-absorbing carbon (6.4%), and nitrate (5%).

### **3.2.2 Spatial Trends in Reconstructed Light Extinction in the United States**

Figure 3.4, based only on IMPROVE data, shows isopleths of the reconstructed aerosol light extinction coefficient (excluding Rayleigh) for the three-year period, March 1996 through February 1999. The highest light extinction (>100 1/Mm) occurs in the eastern United States; the highest extinction for a rural site occurs at Mammoth Cave at 130 1/Mm, then Sipsey Wilderness Area in northern Alabama at 128 1/Mm, followed by Cape Romain and Okefenokee National Wildlife Refuges at 106 1/Mm and 100 1/Mm, respectively. The lowest extinction (<20 1/Mm) generally occurs in the inner-mountain west in the Great Basin and Colorado Plateau regions. The lowest extinction for the contiguous 48 states is at Bridger Wilderness Area and Great Basin National Park at 12 1/Mm. The lowest extinction for the entire United States is at Denali National Park, with an annual extinction of 10 1/Mm. Crater Lake National Park and Jarbidge and Mount Zirkel Wilderness Areas have 13 1/Mm for annual extinction.

Because the majority of Class I areas with IMPROVE monitoring are located in the western United States, spatial coverage of the IMPROVE Network is sparse in the eastern United States. As a result, maps based on IMPROVE data alone, such as Figure 3.4, lack spatial resolution in the eastern United States, where visibility conditions are traditionally the worst. For comparison to Figure 3.4, Figure 3.5 shows the reconstructed aerosol light extinction coefficient using particle mass concentration data from IMPROVE monitoring sites (diamonds) and from monitoring sites in the Clean Air Status and Trends Network (CASTNet) [CASTNet, 1998] (plusses). Details of the

light extinction reconstruction algorithm applied to CASTNet data are given in Appendix A. At the time of this writing, CASTNet data were available only through 1998, therefore Figure 3.5 represents the three-year period, December 1995 through November 1998 instead of March 1996 through February 1999 that is used in the IMPROVE only isopleth maps. However, average aerosol mass concentrations, and hence reconstructed visibility conditions, for the respective time periods represented by Figures 3.4 and 3.5 should be comparable because the time periods for the two maps only differ by three out of 36 months. Figure 3.5 shows the highest light extinction coefficients, in excess of 120 1/Mm, occurring at monitoring locations in the eastern United States and in the general region defined by the Ohio River and Tennessee Valleys. This region of highest light extinction has better spatial resolution and larger geographic extent in the IMPROVE and CASTNet map than in the IMPROVE only map. The lowest extinction (<20 1/Mm) generally occurs in the rural western United States, as indicated by the reconstructed light extinction coefficient derived from both IMPROVE and CASTNet monitoring data in those regions. Similar combined monitoring network light extinction maps for the winter and summer seasons are shown in Appendix A.

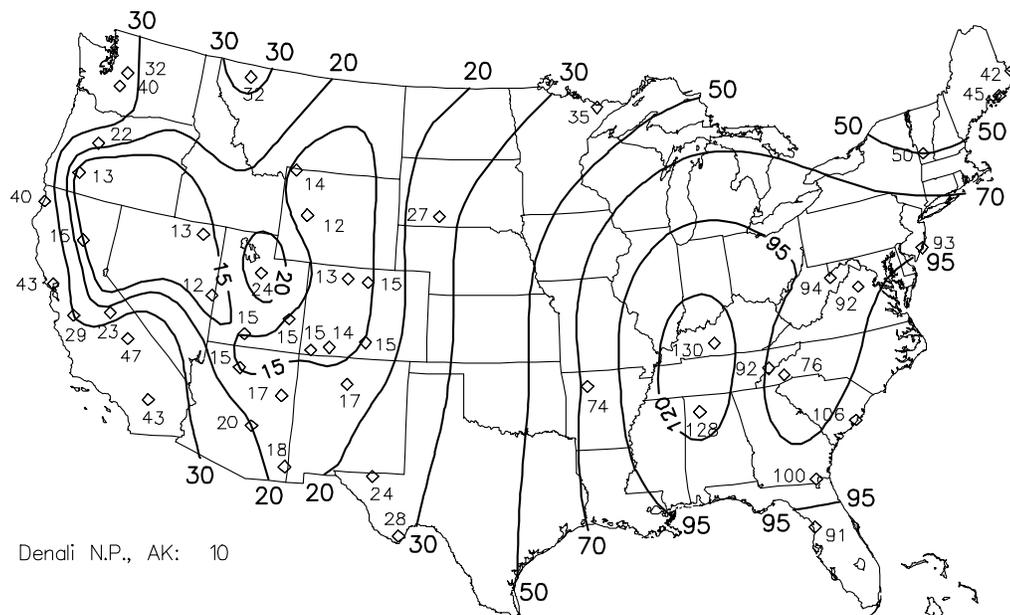
Figure 3.6 shows the sulfate light extinction coefficient averaged over a three-year period of IMPROVE (March 1996 - February 1999). Note that the highest sulfate extinction occurs in the eastern United States, and the lowest sulfate extinction occurs in the Great Basin, Sierra-Nevada and Sierra-Humboldt regions. The major gradient in sulfate light extinction is from the eastern United States to the inner-mountain west. However, there is also a gradient from the Pacific Coastal Mountains and Cascade Mountains regions to the inner-mountain west. Sulfate extinction is more than 60% of the total aerosol light extinction east of the Mississippi, while in the Appalachian and Southeast regions sulfates contribute about three fourths of aerosol light extinction. In the season with the highest sulfate extinction (summer), its contribution to aerosol extinction is even greater at 80-90% in the eastern United States.

Figure 3.7 shows the nitrate light extinction. There is a gradient from east to west, with relatively high nitrate extinction east of the Mississippi River and south of the Great Lakes. However, the strongest gradient is from southern California to the California desert. Nitrate contributions to aerosol light extinction are generally less than 10%, except in California, where nitrate can contribute as much as 39% and the Northern Great Plains and Boundary Waters regions where nitrate extinction contributes to total aerosol extinction in excess of 15%.

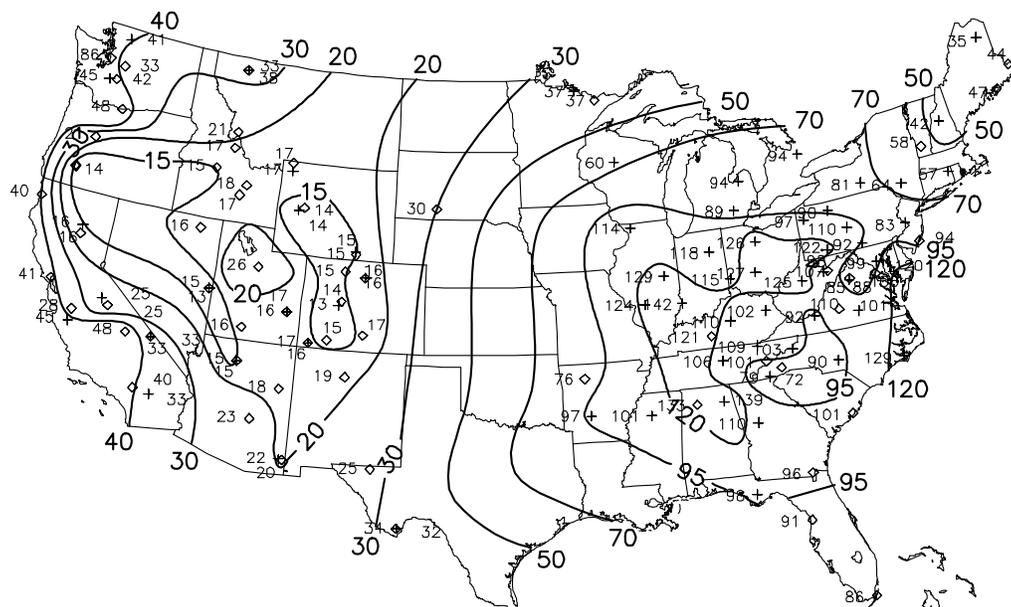
Figure 3.8 shows isopleths of the light extinction due to organics throughout the United States, averaged over the three-year period. Note that extinction caused by organic carbon is largest in the eastern United States, Northern Rocky Mountains and Cascade Mountains regions, and lowest in the Colorado Plateau and Central Rocky Mountain regions. The fraction of aerosol light extinction contributed by organic carbon ranges from a high of 40% in the Sierra Nevada region to less than 15% in the Pacific Coastal Mountains region and eastern United States. Even though organics, on an absolute basis, are higher in the East than West, total aerosol extinction is significantly greater in the eastern United States.

Figure 3.9 shows isopleths of the extinction caused by absorption. Absorption is highest in the Southeast, Southern California, and Cascade Mountains regions and lowest in the inner-mountain west. However, the largest fraction of total extinction attributed to absorption is in the

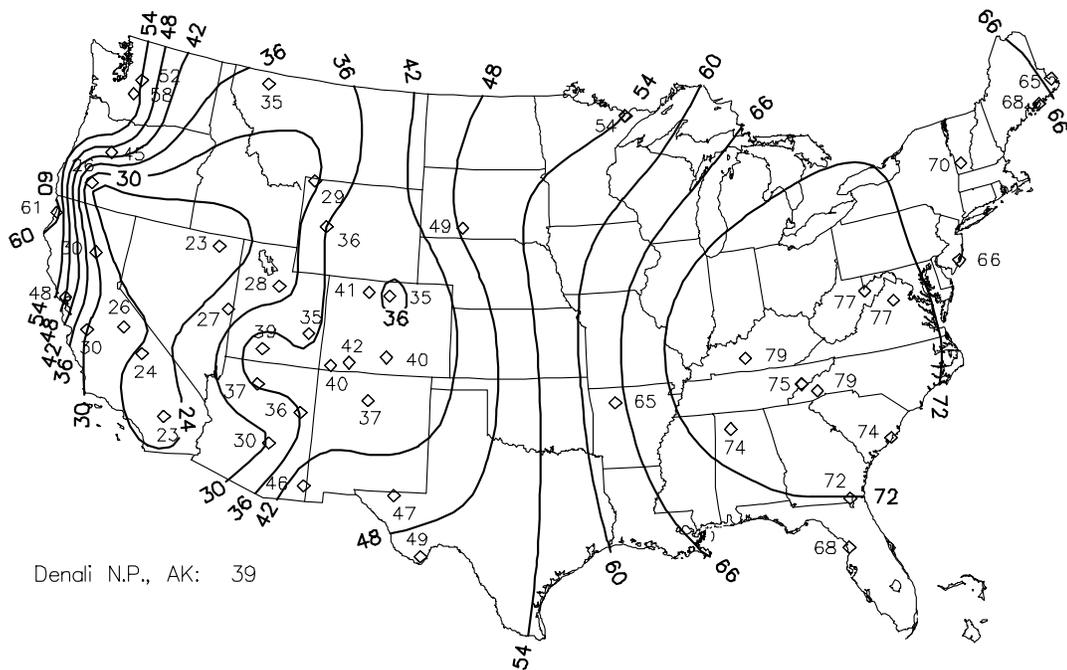
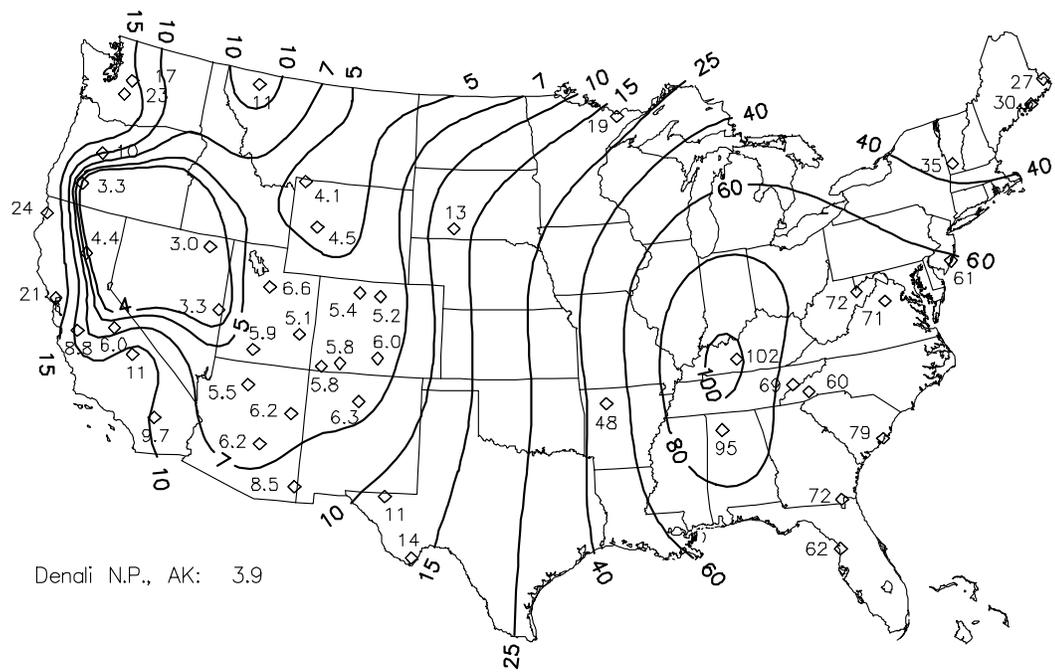
Great Basin, Sierra-Nevada, Sierra-Humboldt, and Colorado Plateau regions, where 10% of extinction is absorption. Except for the coastal regions of northern California, most of the western United States has a contribution from absorption in excess of 6%.



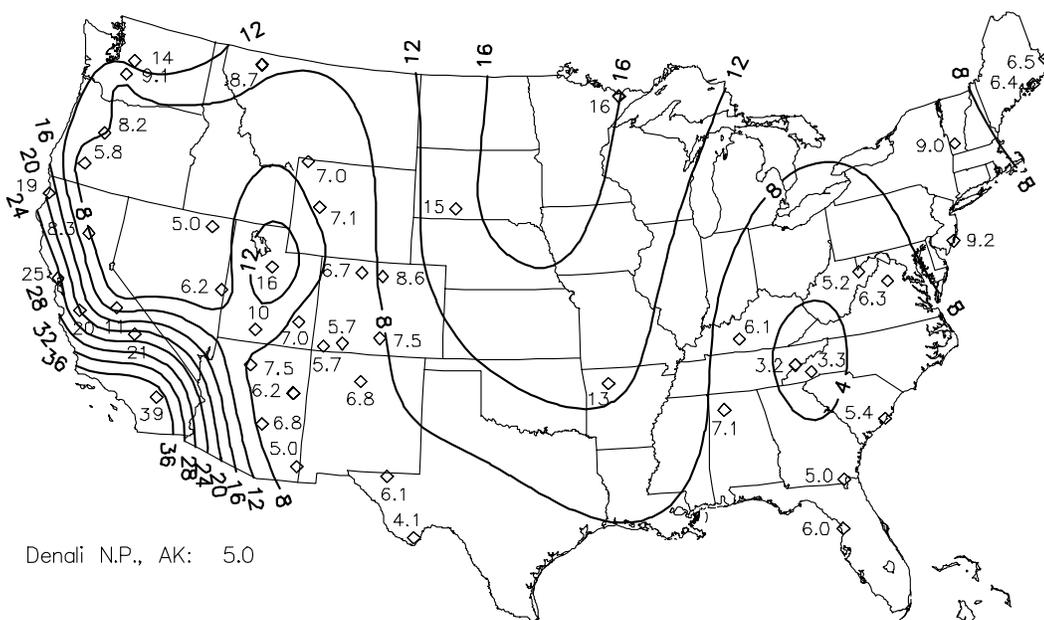
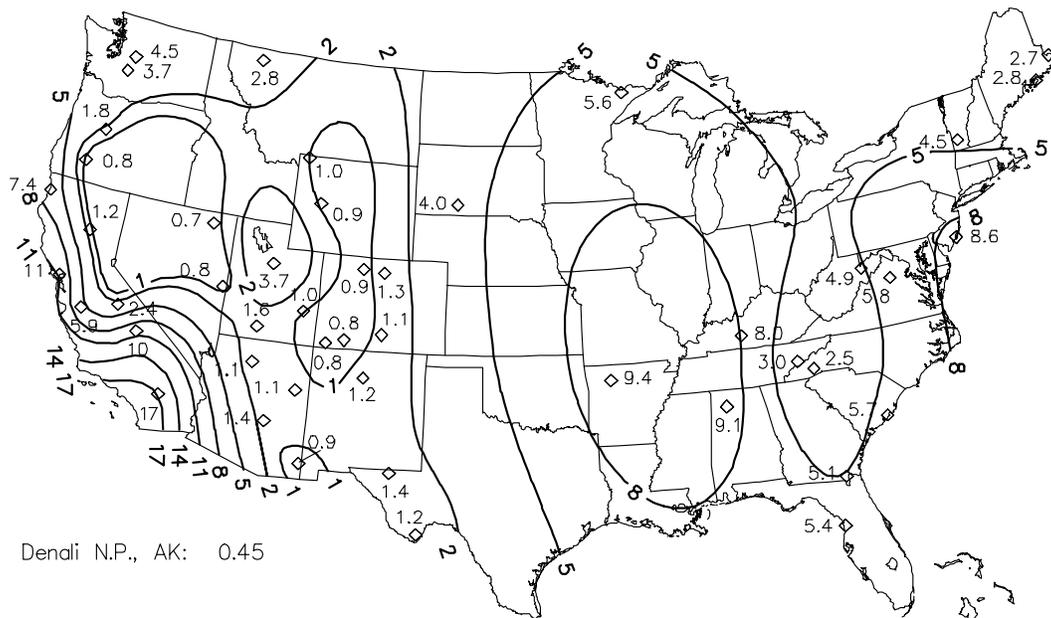
**Figure 3.4** Three-year averages of total reconstructed aerosol (Rayleigh is not included) light-extinction coefficient (1/Mm) for each site in the IMPROVE Network, excluding Washington, D.C.



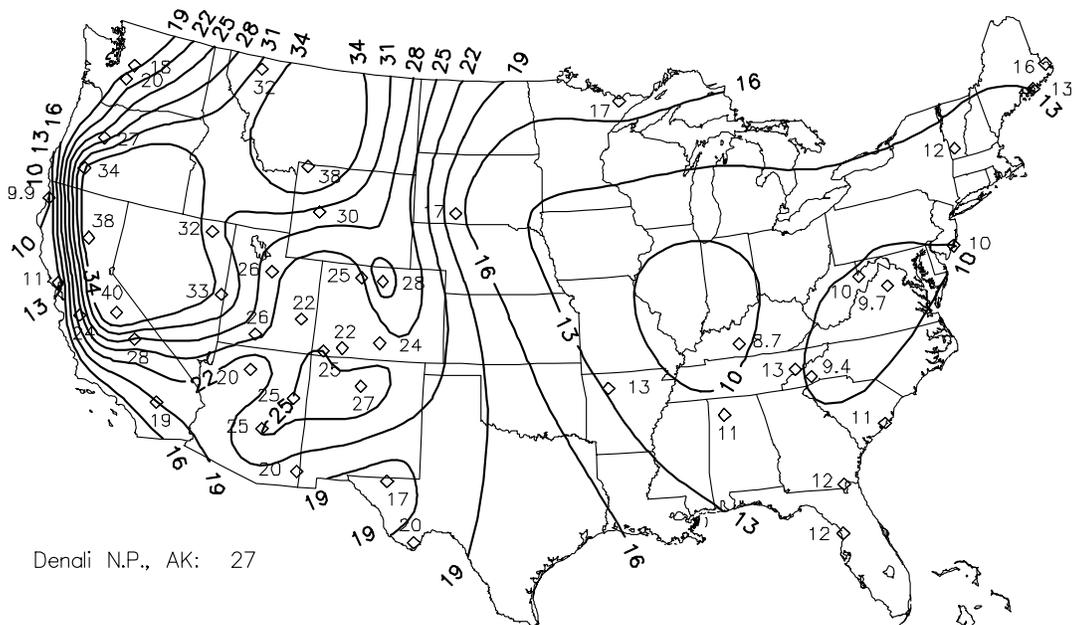
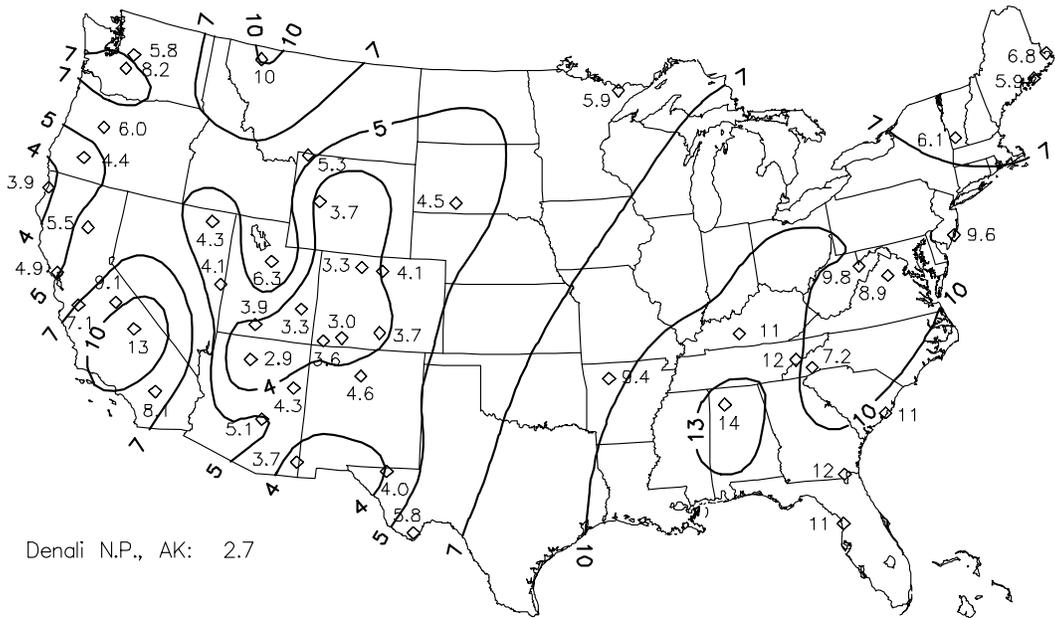
**Figure 3.5** Three-year averages of total reconstructed aerosol light-extinction coefficient (1/Mm) (Rayleigh is not included) for sites in the IMPROVE Network and CASTNet, excluding Washington, D.C.



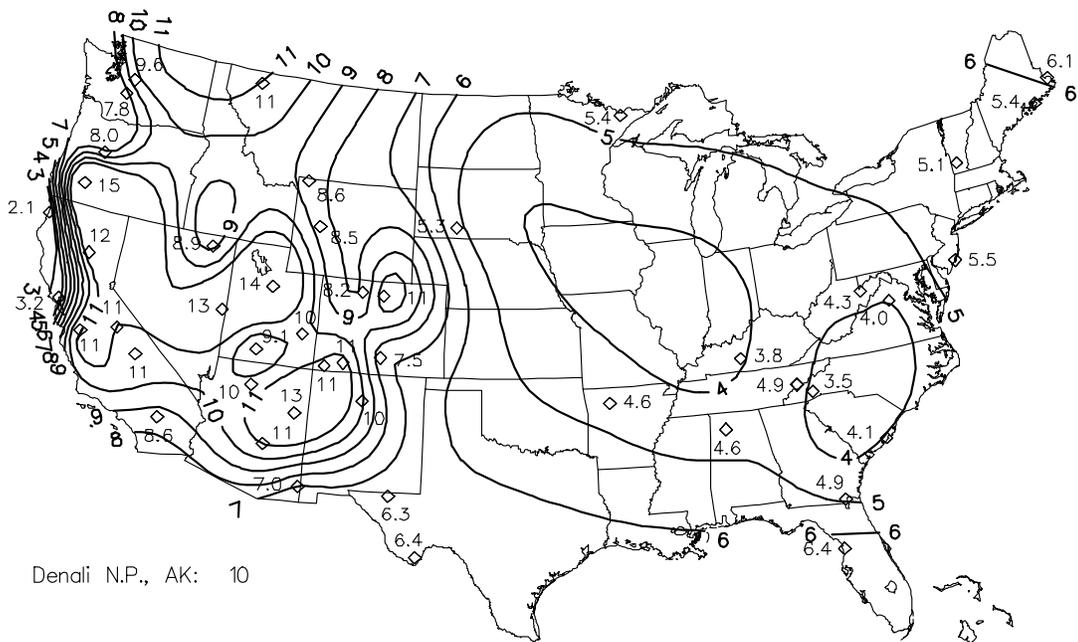
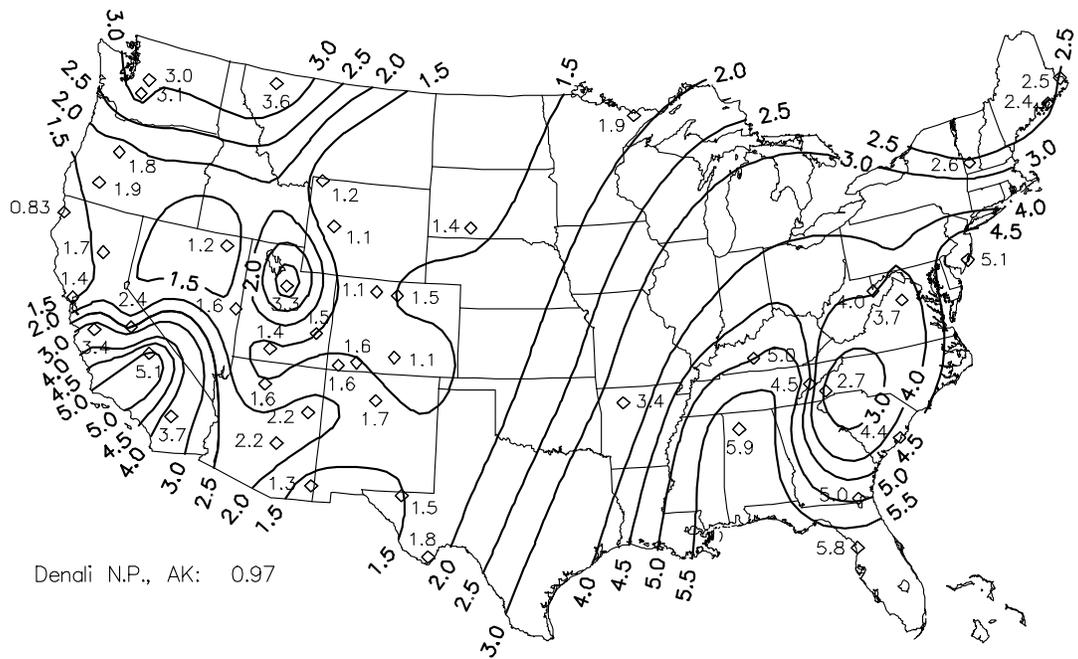
**Figure 3.6** Three-year averages of ammonium sulfate light-extinction coefficient in 1/Mm (top) and sulfate fraction in percent of aerosol light extinction (bottom), for each of the sites in the IMPROVE Network, excluding Washington, D.C.



**Figure 3.7** Three-year averages of ammonium nitrate light extinction coefficient in 1/Mm (top) and nitrate fraction in percent of aerosol light extinction (bottom), for each of the sites in the IMPROVE Network, excluding Washington, D.C.

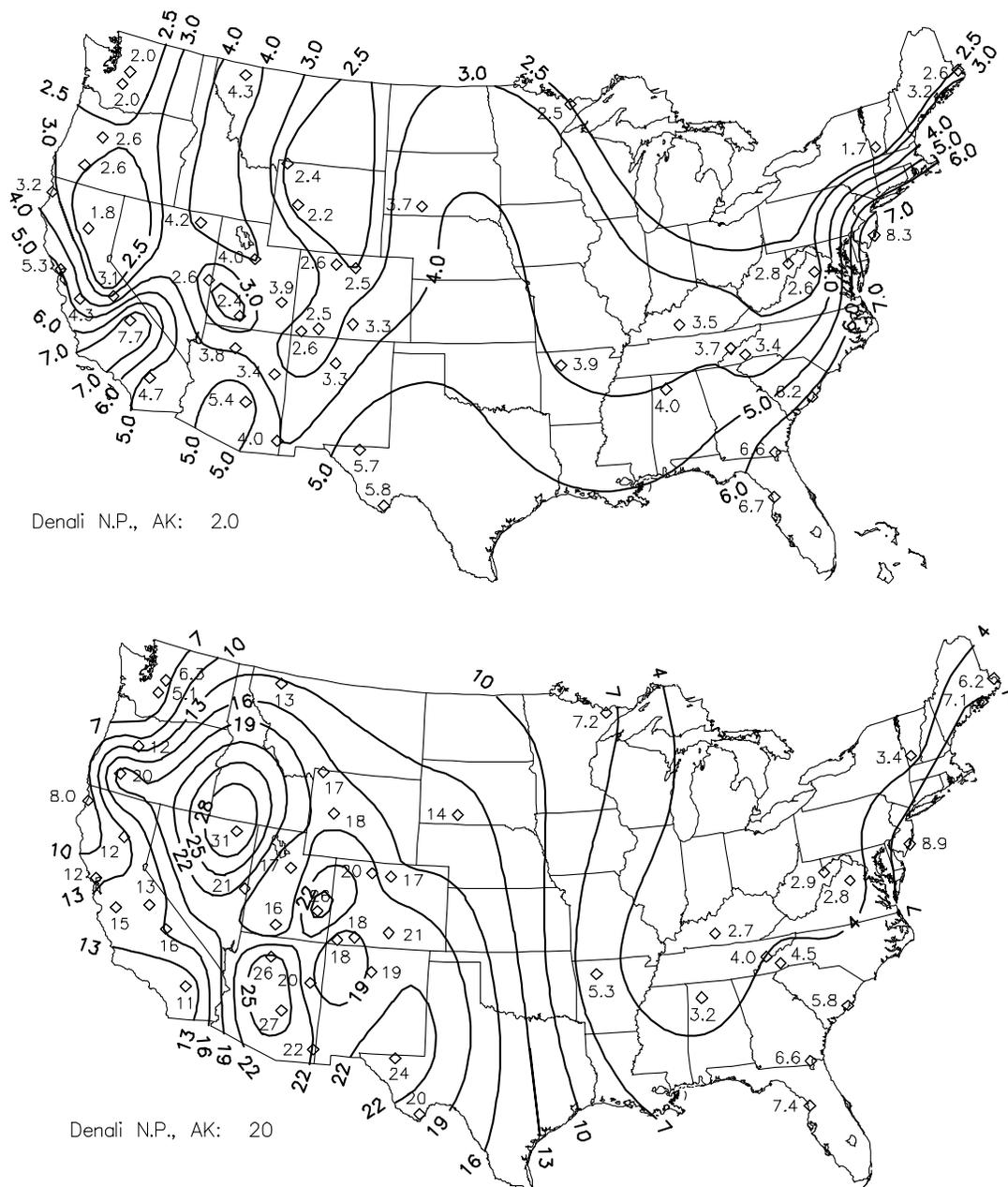


**Figure 3.8** Three-year averages of light extinction due to organic material in 1/Mm (top) and percent of aerosol extinction (bottom), for each of the sites in the IMPROVE Network, excluding Washington, D.C.



**Figure 3.9** Three-year averages of absorption in 1/Mm (top map) and absorption fraction in percent of aerosol light extinction (bottom map), for each of the sites in the IMPROVE Network, excluding Washington, D.C.

Figure 3.10 shows isopleths of light extinction due to coarse material throughout the United States, averaged over the three-year period. Extinction caused by coarse material is highest in Southern California, Sonoran Desert, West Texas, Southeast, and eastern Coastal regions. The least contribution occurs in the Cascade Mountains, Colorado Plateau, and portions of the Central Rocky Mountain regions. The fraction of aerosol extinction contributed by coarse material shows an east-west dichotomy with the eastern United States having the lowest percentages in the Northeast and Appalachian regions at about 3% and the Great Basin area at 20-30%.



**Figure 3.10** Three-year averages of light extinction due to coarse material in 1/Mm (top map) and percent of aerosol extinction (bottom map), for each of the sites in the IMPROVE Network, excluding Washington, D.C.

### 3.2.3 Spatial Trends in Visibility in the United States

Another way of displaying visibility estimates from aerosol data is by using the deciview (dv) scale. The deciview scale was designed to linearly relate to humanly perceived differences in visibility, which is not the case for light extinction. Particle free or Rayleigh conditions have a dv value of zero, and a change of 1 dv is a small but often noticeable change in perceived visibility.

Figure 3.11 shows isopleths of deciviews averaged over the three-year period using only IMPROVE data. There is a broad region that includes the Great Basin, most of the Colorado Plateau and portions of the Central Rocky Mountains that has visibility impairment of less than 10 dv. Moving in any direction from this region generally results in a gradient of increasing deciviews. West of the Sierra Nevada and the Southern California regions, dv values are in excess of 15. To the north a maximal value of 16 dv occurs at Mount Rainier National Park. The Cascade Mountain region and all of the eastern half of the United States have an excess of 13 dv of impaired visibility, and the region east of the Mississippi and south of the Great Lakes have impairment in excess of 23 dv, with the Mid-South region exceeding 25 dv. In fact, the highest annual dv value is reported at Mammoth Cave National Park and Sipsey Wilderness Area with an impairment of 26 dv.

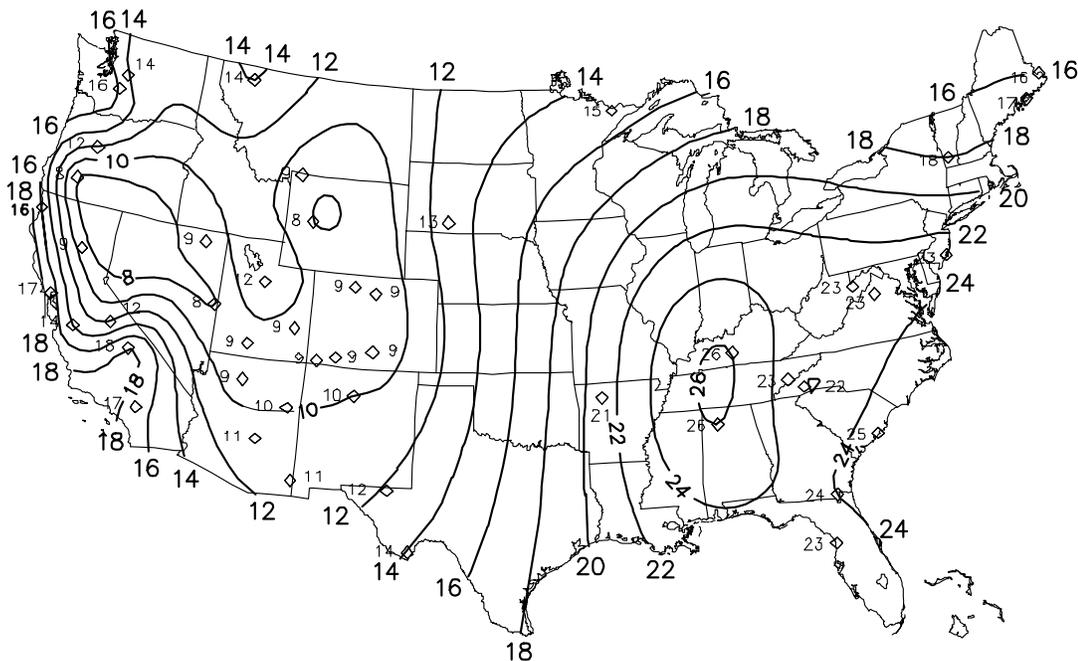
Figure 3.12 is a deciview map calculated from IMPROVE and CASTNet data, analogous to Figure 3.5 showing the reconstructed light extinction coefficient. Spatial resolution of the deciview visibility index is enhanced in the eastern United States using the combined network data. Maximum values ( $\geq 26$  dv) occur along the Ohio River and Tennessee Valleys.

Isopleths of deciviews for the winter, summer, spring, and autumn are shown in Figures 3.13 through Figure 3.16, respectively. The general spatial trend noted above for the annual average generally holds true for each season's average dv trend. Specifically, the least impairment or lowest dv values generally occur in all or part of the Great Basin, Colorado Plateau, and Central Rocky Mountains, with gradients of increasing dv values in any direction. A noticeable exception occurs during the winter and summer (Figures 3.13 and 3.14), at Lone Peak Wilderness Area in Utah, with 13 dv, likely due to haze originating in the urban Salt Lake City area.

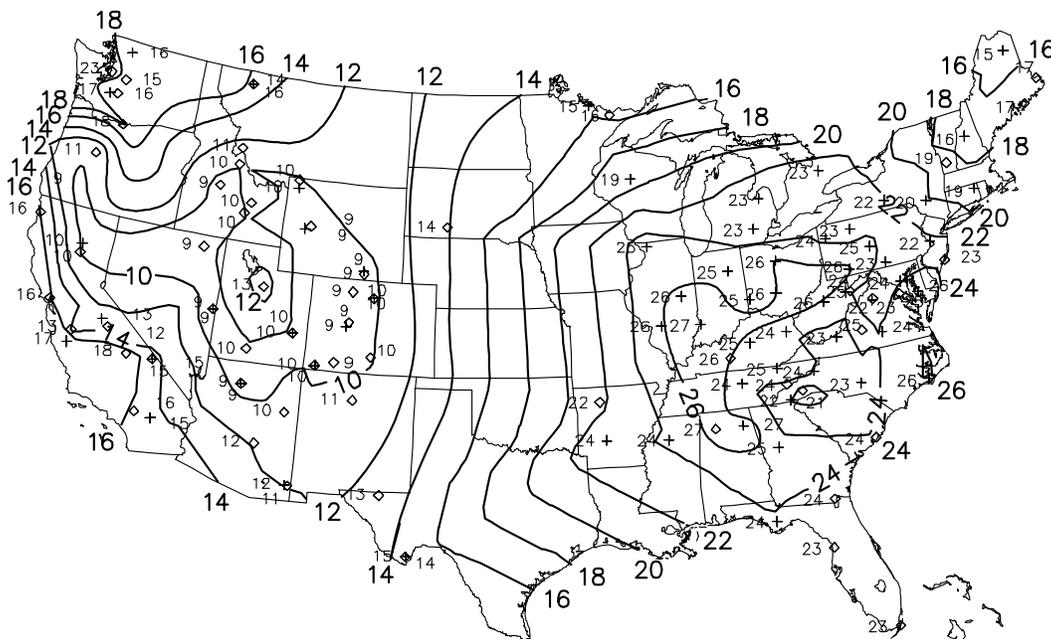
The best visibility in the West occurs during the winter (Figure 3.13) with a minimum average of 4 dv at Jarbidge Wilderness Area. The region of 8 dv or less encompasses a broad expanse that covers the Sierra-Humboldt, Sierra-Nevada, Great Basin, Central Rocky Mountains, and the northwestern half of the Colorado Plateau. In the eastern half of the United States, the seasons of best visibility are winter and spring. In the Northeast and Southeast, the winter is best for visibility, while the Appalachian and Mid-West are variable among sites. However, all sites east of the Mississippi and south of the Great Lakes have impairment in excess of 20 dv for both the spring and winter.

Summertime visibilities (Figure 3.14), except for the Pacific Coastal Mountains, are generally the worst. Only small portions of the Great Basin and Central Rocky Mountains regions have impaired visibilities slightly below 10 dv. In the East, including the Upper Buffalo Wilderness Area, there is a broad region east of the Mississippi with more than 24 dv of impaired

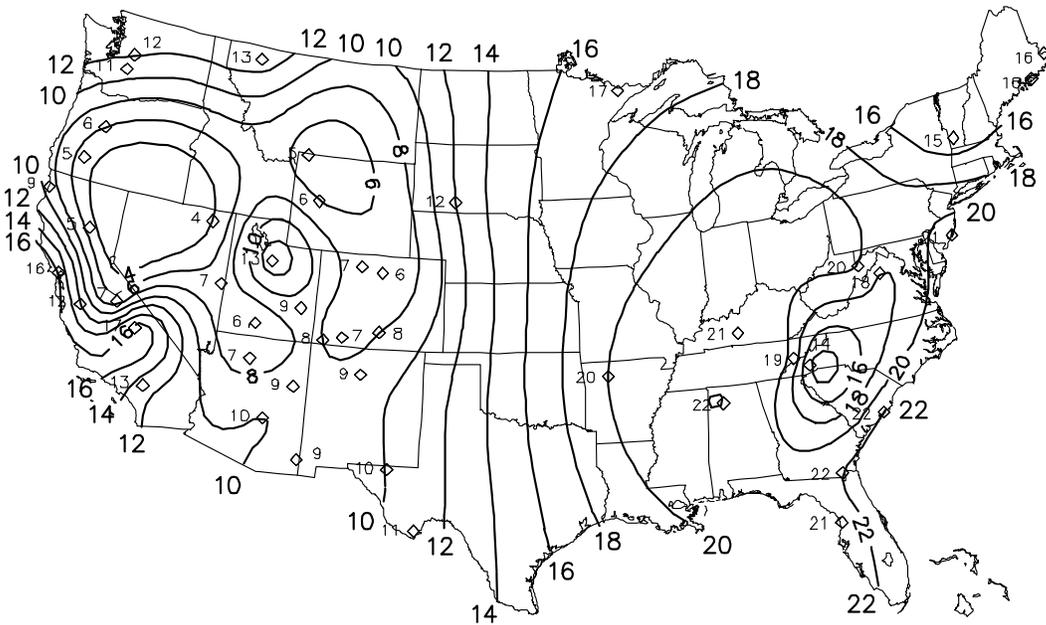
visibility. Moreover, Mammoth Cave National Park and Sipsey Wilderness Area exceed 30 dv in impairment.



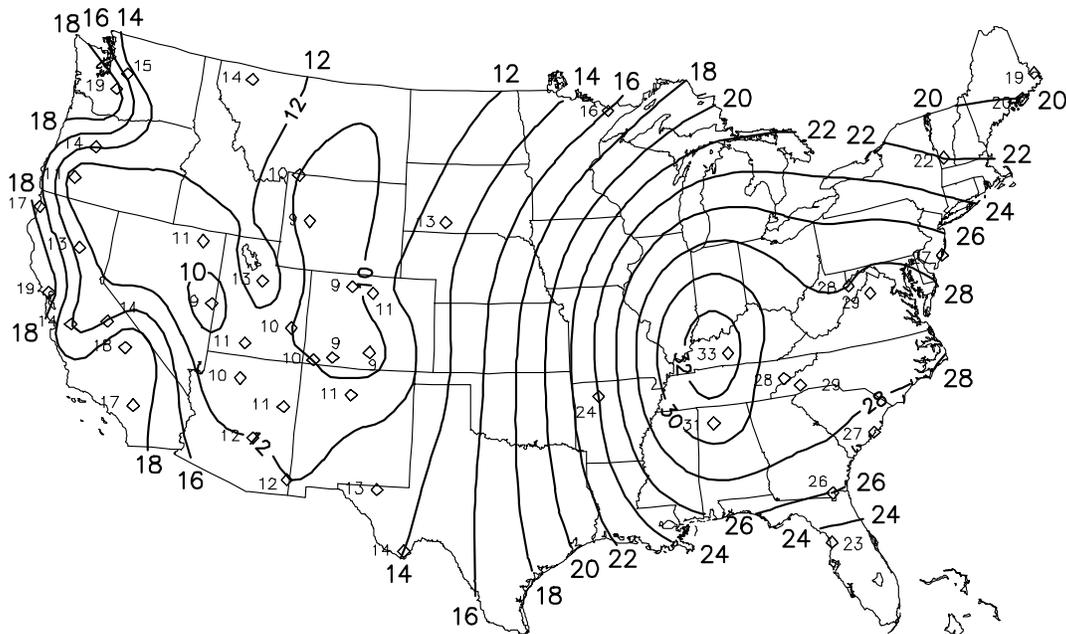
**Figure 3.11** Average visibility impairment in deciviews calculated from total (Rayleigh included) reconstructed light extinction for the three-year period, March 1996 through February 1999, of IMPROVE, excluding Washington, D.C.



**Figure 3.12** Average visibility impairment in deciviews calculated from total (Rayleigh included) reconstructed light extinction for the three-year period, December 1995 through November 1998, of IMPROVE and CASTNet, excluding Washington, D.C.

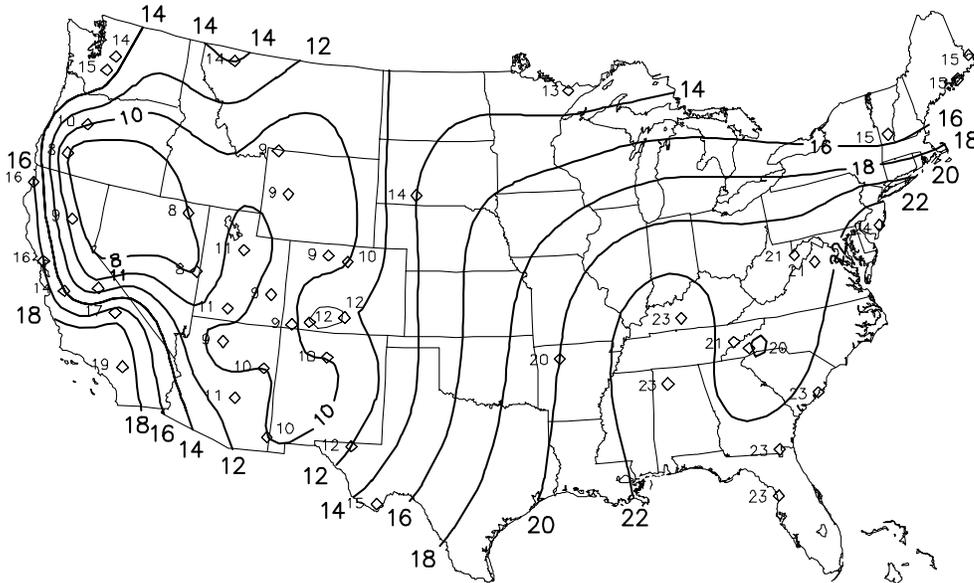


**Figure 3.13** Average winter visibility impairment in deciviews calculated from total (Rayleigh included) reconstructed light extinction for the three-year period, March 1996 through February 1999, excluding Washington, D.C.

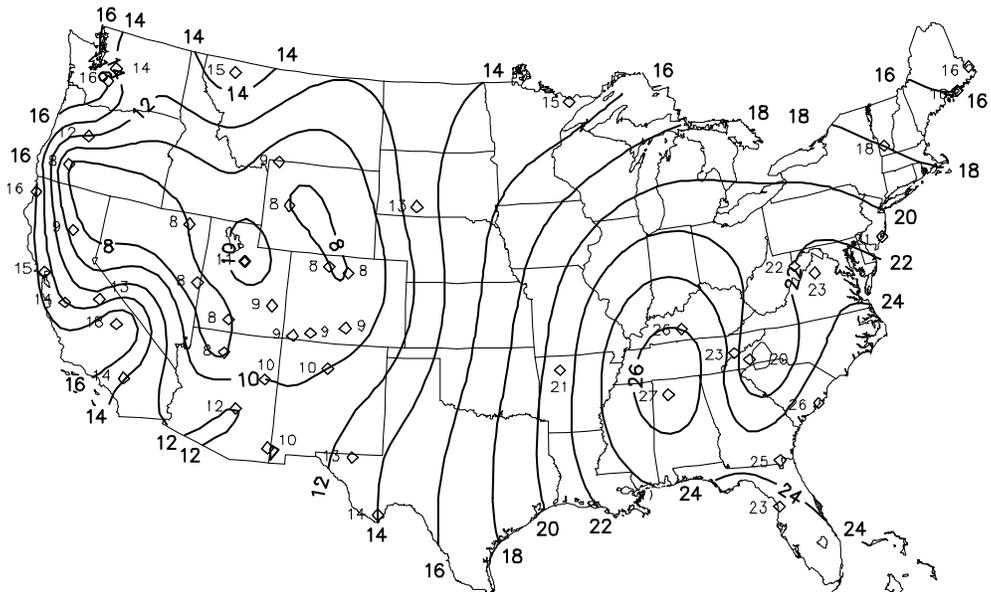


**Figure 3.14** Average summer visibility impairment in deciviews calculated from total (Rayleigh included) reconstructed light extinction for the three-year period, March 1996 through February 1999, excluding Washington, D.C.

Visibility impairment in the spring (Figure 3.15) and autumn (Figure 3.16) are quite comparable. However, in the autumn the East is generally hazier than spring, while in the inner-mountain west, autumn is generally less impaired, particularly in the Central Rocky Mountains region. Southern California has better visibility in the autumn.



**Figure 3.15** Average spring visibility impairment in deciviews calculated from total (Rayleigh included) reconstructed light extinction for the three-year period, March 1996 through February 1999, excluding Washington, D.C.



**Figure 3.16** Average autumn visibility impairment in deciviews calculated from total (Rayleigh included) reconstructed light extinction for the three-year period, March 1996 through February 1999, excluding Washington, D.C.

### 3.3 SUMMARY

The following are the major patterns in light extinction reconstructed from aerosol measurements and relative humidity during the three-year period of IMPROVE (March 1996-February 1999):

- (1) Spatial Patterns. Following the patterns observed in fine aerosol concentrations, reconstructed light extinction is highest in the eastern United States and in urban California and lowest in the nonurban west.
- (2) Major Contributors to Light Extinction. Fine aerosols are the most effective in scattering light and are the major contributors to light extinction. In most cases, the sulfate component of fine aerosol is the largest single contributor to light extinction. This is because sulfate, being hygroscopic, generally has a higher light extinction efficiency than other species due to associated liquid water. This is especially true in the eastern United States, where relative humidity is high. In the Appalachian Mountains (Shenandoah and Great Smoky Mountains), sulfate accounts for nearly 80% of the total aerosol light extinction throughout the year, and more during the summer months. Sulfates contribute the least in the Great Basin region at about 25%, while along the Rocky Mountains the contribution is about 30-40%. In the Cascade Mountain region sulfates contribute significantly at 50-60%. Sulfates are the largest single contributor to light extinction in 17 of the 21 regions and are about comparable to organics in two of these regions, Northern Rocky Mountains and Wasatch.
- (3) Nitrates are the single largest contributor to extinction in the Southern California region at 39% but also contribute significantly along the coastal areas of California at about 20-25%. Nitrates are 16% of extinction at Lone Peak Wilderness Area near Salt Lake City, while in the rest of the United States it is less than 10%.
- (4) Organics are, in general, the second largest contributor to total aerosol extinction. It is the largest contributor in the Great Basin, Sierra-Humboldt, and Sierra Nevada regions at 33%, 36%, and 32%, respectively. It is the largest contributor at Yosemite National Park at 40% and on the order of about 10% in most of the eastern United States. In the Central Rocky Mountains and on the Colorado Plateau its contribution to extinction is about 20-25%.
- (5) Light-absorbing carbon is on the order of about 10% in much of the western United States and on the order of 5% east of the Mississippi. In the three regions where organics are the largest contributors to extinction, the sum of organic and light absorbing carbon, or the contribution of carbon in general, to extinction is 40-50%.
- (6) Fine and coarse soil/dust in the eastern United States is generally less than 5%, while in the Sonoran Desert, West Texas, Great Basin regions its contribution to extinction is on the order of 20-30%. In the Cascade Mountains region it is about 5%. In the rest of the United States soil/dust contributes between about 10 and 20% of extinction.
- (7) Generally, reconstructed light extinction is highest in summer and lowest in winter; however, there are many exceptions to this general rule. Higher extinction occurs in summer generally

because of elevated sulfate and carbonaceous aerosol concentrations. Also, higher average RHs occur in the East during the summer, which increases extinction.

- (8) The general spatial trend noted above for the annual average visibility levels generally holds true for each season's average visibility as well. Specifically, the least impairment occurs in all or part of the Great Basin, Colorado Plateau, and Central Rocky Mountains, with gradients of increasing  $dv$  values in any direction. The best visibility occurs during the winter and the worst in the summer. Visibility impairment in the spring and autumn are comparable.

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