CHAPTER 6

SPATIAL AND SEASONAL DISTRIBUTION OF RECONSTRUCTED LIGHT EXTINCTION

In the previous chapter the measurements of aerosol concentrations and chemical composition during the first three years of IMPROVE were presented. In this chapter, these aerosol measurements and current understanding of the light extinction efficiencies of aerosol components are used to derive the reconstructed light extinction coefficient. In addition, the relative contribution of various aerosol components to total light extinction are combined into a light extinction budget. The next chapter presents the results of direct transmissometer measurements of the light extinction coefficient.

6.1 Reconstructing Light Extinction from Aerosol Measurements

To review the discussion presented in Chapter 1 (see Equation 1.2), the light extinction coefficient is the sum of several components:

$$b_{ext} = b_{scat} + b_{abs} = b_{Ray} + b_{sp} + b_{ag} + b_{ap} \qquad (6.1)$$

where
b_{ext} = light extinction coefficient,
b_{scat} = light scattering coefficient,
b_{abs} = light absorption coefficient,
b_{Ray} = Rayleigh light scattering coefficient,
b_{sp} = light scattering coefficient due to particles,
b_{ag} = light absorption coefficient due to gases, and
b_{ap} = light absorption coefficient due to particles.

The Rayleigh scattering coefficient (b_{Ray}) is the light scattered by molecules of gas in the natural atmosphere (i.e., oxygen and nitrogen, primarily). The Rayleigh scattering coefficient will vary with atmospheric pressure. For this report we assume the Rayleigh scattering coefficient is 10 Mm^{-1} (inverse megameters) at all sites.

The light absorption coefficient due to gases (b_{ag}) is dominated in the atmosphere by the effect of nitrogen dioxide (NO_2) gas. For this report, we assume this component is negligible. This assumption may not be correct at locations close to significant NO_x emission sources (e.g., urban areas or power plants).

In most instances, b_{sp} and b_{ap} are primarily responsible for visibility reduction. Single particle scattering and absorption properties can, with a number of limiting assumptions, be calculated theoretically using Mie theory (vandeHulst, 1981). However, before such calculations are carried out, suitable boundary conditions must be specified. Typically aerosol models assume:

- External mixtures - particles exist in the atmosphere as pure chemical species which are mixed without interaction;
- Multi-component aerosols - single particles are made up of two or more species. If the chemical species are combined in fixed proportions independent of particle size, the aerosol is referred to as internally mixed. Other models assume solid cores with deposited shells of various thickness and composition.

If an aerosol is mixed externally, or for an internally mixed aerosol if the index of refraction is not a function of composition or size, and the aerosol density is independent of volume, then aerosol extinction due to particles can be related in a linear fashion to particle mass concentration (Ouimette and Flagan, 1982).

The approach used here to estimate extinction assumes externally mixed aerosols. The light extinction coefficient can then be calculated (or reconstructed) from aerosol concentrations by taking Equation 6.1 and describing the light extinction contributed by aerosol component (*i*) as the product of the aerosol component's concentration (C_i) and its light extinction efficiency (b_i). Thus, the total light extinction coefficient is simply the sum of the light extinctions of each aerosol component:

$$b_{ext} = b_{Ray} + \sum \beta_i C_i \qquad (6.2)$$

The efficiencies used for the various components are discussed below. Any apportionment by this means can only be judged in the context of whether or not it is reasonable, and whether apportionment of mass to extinction is consistent with measurements of scattering and absorption (White et al., 1986).

Equation 6.2 can be cast into the following form for the aerosol components measured as part of the IMPROVE program:

$$\begin{aligned} b_{ext} &= b_{Ray} + \beta_{sulfate}[SULFATE] + \beta_{NITRATE}[NITRATE] + \beta_{OC}[OCM] \\ &+ \beta_{LAC}[LAC] + \beta_{SOIL}[SOIL] + \beta_{CM}[CM] \end{aligned} \qquad (6.3)$$

where b_{ext} is the total light extinction coefficient (in Mm^{-1}), b_{Ray} is the Rayleigh scattering coefficient (10 Mm^{-1}), the â's are the light extinction coefficients for each component (in m^2/g), and the parameters in brackets ([ ]) are the concentrations of the aerosol components (in ìg/m^3).

The values of light extinction efficiency (in m^2/g) used in this report are as follows:

Sulfates and Nitrates	3 $f_T(RH)$
Organic Carbon	3 $[1 + f_H(RH)]/2$
Light Absorbing Carbon	10
Fine Soil	1
Coarse Particles	0.6

The functions $f_T(RH)$ and $f_H(RH)$ are correction factors to account for the liquid water that may be part of the hygroscopic aerosol components (sulfate, nitrate, and some organic carbon). These functions are dependent on the relative humidity (RH) at the given site. These functions are discussed in Section 6.2 (a detailed exposition is given in Appendix H).

In this report, we assume that coarse particles and fine soil particles are from a single natural source, windblown dust. Thus, the extinction calculated for these two components were combined into a single category and is reported as coarse extinction.

Figure 6.1 shows schematically how the various aerosol components are used to reconstruct the total light extinction due to aerosols. Total light extinction is then the sum of aerosol light extinction, Rayleigh scattering, and nitrogen dioxide light absorption.

6.2 Effect of Relative Humidity on Extinction Efficiencies

A complicating factor is that soluble fine aerosol species absorb water from the atmosphere and grow in size. This behavior can be modeled as a function of relative humidity (RH) assuming thermodynamic equilibrium (Tsay et al., 1991). It is known that ammonium sulfate aerosols will abruptly go into solution at a specific RH. This process is known as deliquescence. The reverse phase change, crystallization, when the liquid evaporates from the droplets, occurs at a lower RH and a slower rate. The growth and phase change of the particles, of course, affects their light scattering efficiency. In general, the higher the RH, the greater the scattering by sulfate and nitrate aerosols. The relationship between RH and scattering efficiency for sulfate aerosols, referred to as $f_T(RH)$, is parameterized from curves published by Tang et al. (1981) and shown in Figure 6.2. Tang's curves, calculated theoretically for aerosols of different size distributions under conditions of increasing RH, have sharp discontinuities at 62% RH for ammonium nitrate, and at 80% for ammonium sulfate, the deliquescence points for these species.

Such aerosol mixtures exhibit the hysterisis effect (illustrated in Figure 6.3) in which more water is held in the aerosol phase then equilibrium considerations would dictate. In the atmosphere, the situation is further complicated by internally mixed soluble aerosols which may go through several stages of growth (Wexler and Seinfeld, 1991). The RHs at which these stages occur depend on the mixture, but in general are between 50% and 80% (Tang et al., 1981). Tang's curves were smoothed between the deliquescence point and 30% RH (see Figure 6.3) because: (1) mixtures of ammonium nitrate and ammonium sulfate species have been shown to be hygroscopic below single species values (Sloane, 1985; Stelson and Seinfeld, 1982); (2) it is not known whether the ascending or descending limb of the hysteresis curve applies for a particular aerosol sample (i.e.,whether aerosol water concentrations areat equilibrium or at

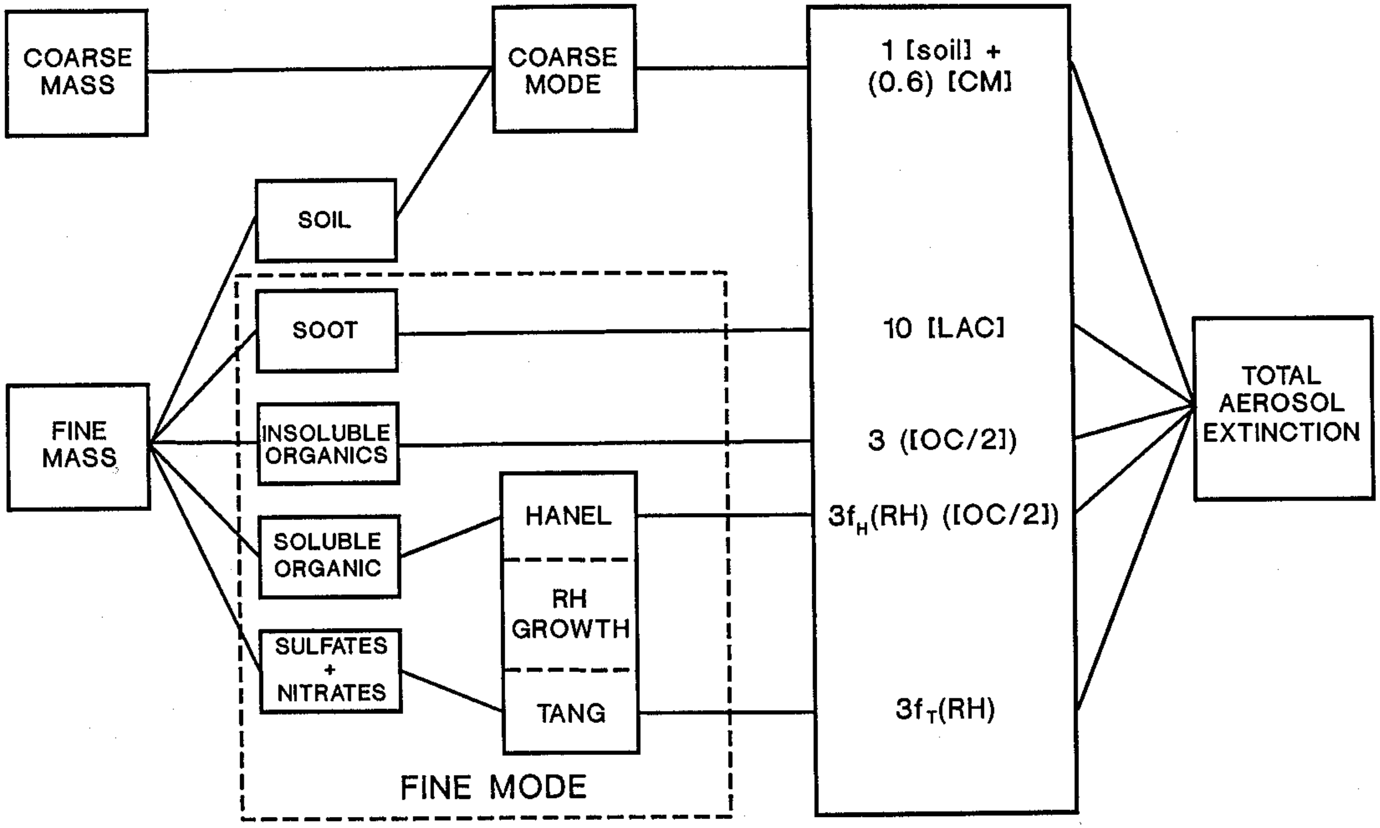


Figure 6.1. Schematic flow diagram showing how light extinction is reconstructed from measurements of aerosol concentration and relative humidity.

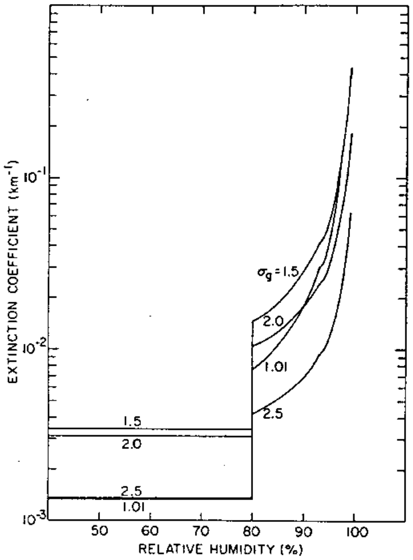


Figure 6.2. Dependence on relative humidity of light extinction coefficient for 1 $\mu g/m^3$ of ammonium sulfate (with size distributions characterized by the indicated geometric standard deviations (r_g). Note the deliquescence point at 80% relative humidity. Source: Tang (1980), Tang et al. (1981).

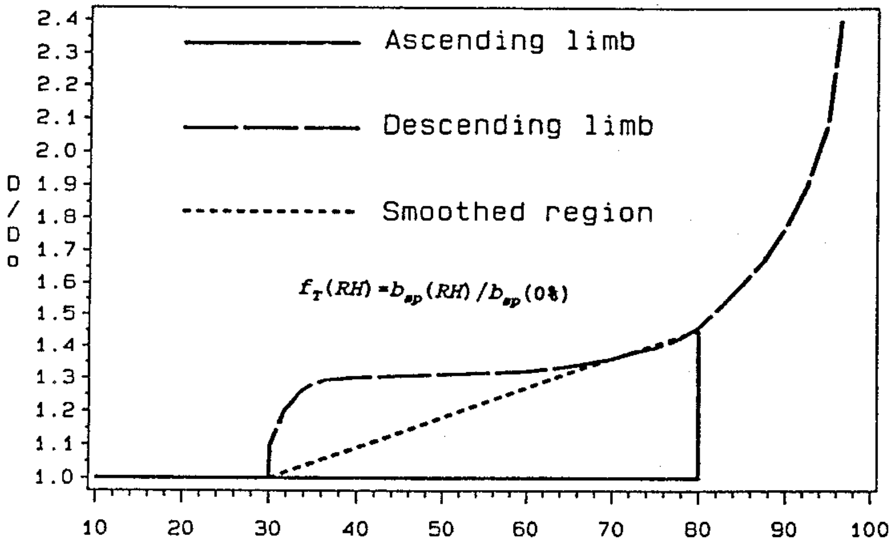


Figure 6.3. Hysteresis effect for ammonium sulfate. As relative humidity increases (see ascending limb), water is not taken up into the aerosol phase until 80% RH. However, for decreasing relative humidity (see descending limb), more water is retained in the aerosol phase than equilibrium considerations would indicate. The relationship between the ascending and descending limbs was used to model RH dependence of sulfate and nitrate light scattering efficiency.

super-equilibrium); and (3) the growth factor and light scattering efficiency for ambient aerosols has previously been observed to be rather smooth (Wexler and Seinfeld, 1991; Sloane, 1985).

The effect of relative humidity and aerosol water on sulfate and nitrate light scattering is accounted for with a RH correction factor, $f_T(RH)$:

$$f_T(RH) = b_{sp}(RH)/b_{sp}(0\%) \qquad (6.4)$$

where $b_{sp}(0\%)$ and $b_{sp}(RH)$ are the dry and wet scattering, respectively.

Soluble organics are presumed to be less hygroscopic than ammonium sulfate and ammonium nitrate. Therefore, a correction factor parameterized to data published by Hanel (1982), $f_H(RH)$, was derived. $f_H(RH)$ produces a smaller correction per unit of soluble material and is used to model the influence of RH on soluble organic material. In this report, it is assumed that half the organics are water soluble and that half are not.

Light extinction budgets and mass budgets involve averaging samples collected over a time interval. The extinction/mass budget represents the average contribution of each aerosol species to the average extinction/mass for the time interval. When soluble aerosols dominate $PM_{2.5}$, the distribution of RH over the interval becomes an issue. Failure to consider the distribution of RH can have significant effects on the average extinction attributed to soluble aerosols.

Mass budgets, for a particular time interval, are calculated by finding the average concentrations of the individual species of fine mass, then dividing each by the sum of the averages. If the aerosol data can be time matched with RH data, then light extinction budgets can be calculated in a parallel fashion. Specifically, a light extinction for each species and each sample can be calculated. Thus, the average light extinction due to each species over the time interval can be estimated.

If collocated and time-matched RH data are not available, but reliable estimates of the average RH over the time interval are, then a first approximation of an average light extinction for a given species can be made. One initial approach would be to apply the RH correction factor associated with the average RH to estimate the average extinction due to a soluble species. However, it can be demonstrated that for sites where the average RH is high, this approach will seriously underestimate the average extinction of a soluble aerosol when the soluble aerosol concentration is independent of RH (see Appendix H). This is due to the convex and highly nonlinear nature of the aerosol growth curves and the subsequent functions, $f_T(RH)$ and $f_H(RH)$. In the case of Tang's or Hanel's function Equation 6.5 holds

$$f_T\overline{(RH)} \leq \overline{f_T(RH)} \qquad (6.5)$$

Moreover, if the distribution of soluble species concentrations are independent of RH, then

$$\overline{f_T(RH)c} \approx \overline{f_T(RH)}\left(\overline{c}\right) \qquad (6.6)$$

Equality would occur as a limiting value when the sample size increases without bound.

In this report, light extinction due to a soluble species at site *s* is derived using hourly RH values less than or equal to 98% and the equation is

$$b_{ext} = \beta F_{T,s}\,\overline{c} \qquad (6.7)$$

where

$$F_{T,s} = \overline{f_T(RH_s)} \qquad (6.8)$$

$F_{H,s}$ is defined similarly. Using Equation 6.3, extinction budgets for a time interval may be calculated by replacing $f_T(RH_s)$ with $F_{T,s}$ and $f_H(RH_s)$ with $F_{H,s}$ and by using the average concentration of each species over the time interval as the mass concentration.

Using the data for the collocated sites, Figure 6.4 has the plot of Tangs's RH dependent factor, as defined by Equation 6.8, versus annual average RH for the 20 IMPROVE sites with RH and light extinction measurements. A quadratic curve was fitted to the annual and seasonal data as defined by,

$$F = b_0 + b_1\left(\overline{RH}\right) + b_2\left(\overline{RH}\right)^2 \qquad (6.9)$$

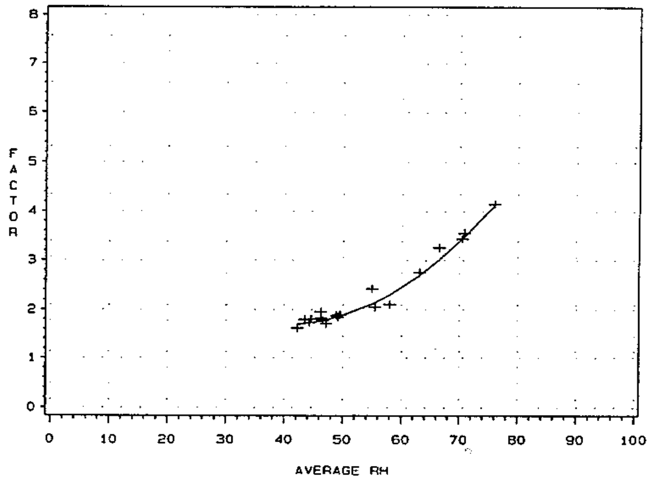


Figure 6.4. **Dependence on average site relative humidity of the relative humidity correction factor for sulfate ($F_{T,s}$) for the IMPROVE sites with relative humidity measurements.**

Tables 6.1a and 6.1b show the results of the regressions for Tangs's and Hanel's weighted correction factors. The high r^2 values arise from the fact that the noise in the relationship is due primarily to differences in the RH distributions between sites. More explicitly, if two sites had the same average RH, their weighted factors would be the same if their RH distributions were identical.

Table 6.1. Parameters of the best-fit quadratic equation relating the relative humidity light extinction correction factors (F_T and F_H) to average site relative humidity ($F = b_o + b_1RH + b_2RH^2$).

(a) F_T for Sulfates and Nitrates (Tang)

Season	b_o	b_1	b_2	r^2
Annual	4.63±0.93	-0.148±0.033	0.0019±0.0003	0.98
Autumn	3.01±0.711	-0.094±0.025	0.0014±0.0002	0.98
Spring	2.42±0.54	-0.070±0.021	0.0012±0.0002	0.98
Summer	2.06±0.382	-0.059±0.015	0.0011±0.0001	0.98
Winter	5.90±2.39	-0.181±0.078	0.0021±0.0006	0.88

(b) F_H for Soluble Organics (Hanel)

Season	b_o	b_1	b_2	r^2
Annual	3.93±0.702	-0.119±0.025	0.001±0.0002	0.97
Autumn	2.69±0.527	-0.078±0.019	0.001±0.0002	0.98
Spring	2.18±0.417	-0.058±0.017	0.0009±0.0001	0.97
Summer	1.85±0.281	-0.047±0.011	0.001±0.0002	0.98
Winter	5.20±1.96	-0.154±0.061	0.002±0.0005	0.84

Using the results of the quadratic regressions, annual and seasonal weighted factors were calculated for 16 additional sites by estimating their annual and seasonal average RH from weather service RH contour maps (NOAA, 1978) (Figure 6.5a). Figure 6.5b shows a contour map showing the annual RH dependent factor isopleths for the continental United States.

6.3 Spatial Distributions of Reconstructed Light Extinction and Light Extinction Budgets

Spatial patterns in the reconstructed light extinction should be somewhat similar to those observed for aerosols since reconstructed light extinction is calculated from aerosol concentrations. However, since light extinction efficiencies of sulfates and nitrates are larger than other fine aerosols because of associated water, and since light absorbing carbon has a relatively high extinction efficiency, the extinction budgets should be different from fine aerosol budgets.

Figure 6.6 shows the magnitude of total reconstructed aerosol light extinction (non-Rayleigh) coefficient based on the three years of IMPROVE aerosol data for each of the 19 regions in the United States. In a series of five bar graphs for each region, the magnitude of reconstructed aerosol light extinction is shown for each season and for the entire period (annual). The portions contributed by ammonium sulfate, ammonium nitrate, organic carbon, light absorbing carbon, and windblown dust (the fine soil and coarse mass contributions) are shown by different bar shadings. Note that the highest reconstructed extinctions occur in the eastern U.S., while the lowest extinctions occur in the non-urban West. Significant seasonal variation in reconstructed light extinction can be observed, especially in the Appalachian Mountains and in Southern California.

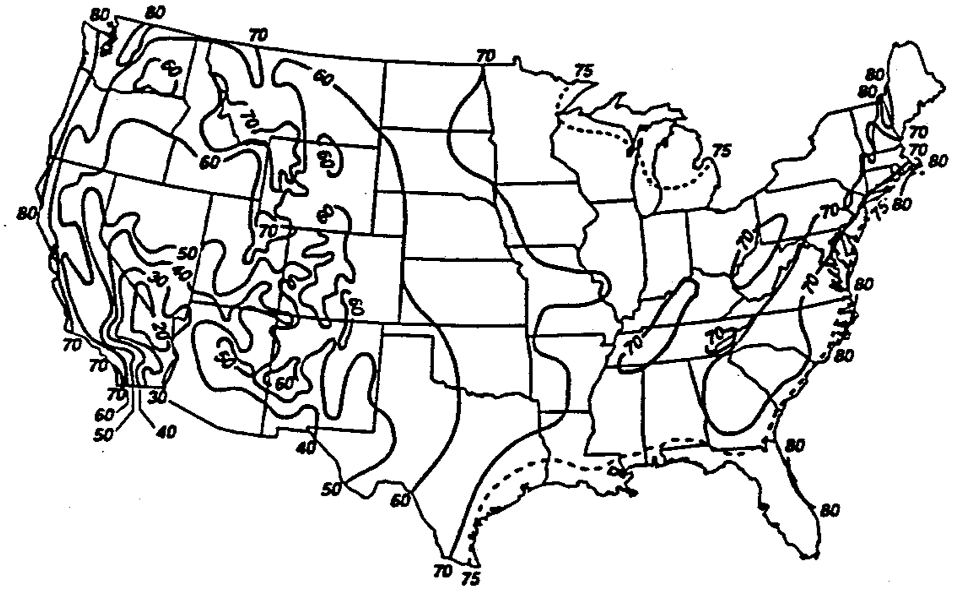
Figure 6.7 shows the light extinction budget or the relative fraction of total aerosol (non-Rayleigh) extinction caused by the various aerosol components. Note that the contribution of sulfate to total aerosol extinction is usually the largest single contributor for all sites east of New Mexico plus Alaska and Hawaii. In the East, sulfates usually contribute more to extinction than all other species combined. At many of the sites in the Pacific Northwest, organic carbon is the largest single contributor.

Figure 6.8 shows isopleths of the total reconstructed light extinction coefficient (including Rayleigh) for the entire three-year period, March 1988 through February 1991. Because of the less dense coverage in the eastern U.S., the isopleths are dashed to indicate greater uncertainty in their placement. The highest light extinction (>100 Mm^{-1}) occurs in the eastern United States. The lowest light extinction (<30 Mm^{-1}) occurs in the non-urban Southwest. Extinctions are also relatively high near the Los Angeles and San Francisco metropolitan areas of California and, to a lesser extent, in the Pacific Northwest.

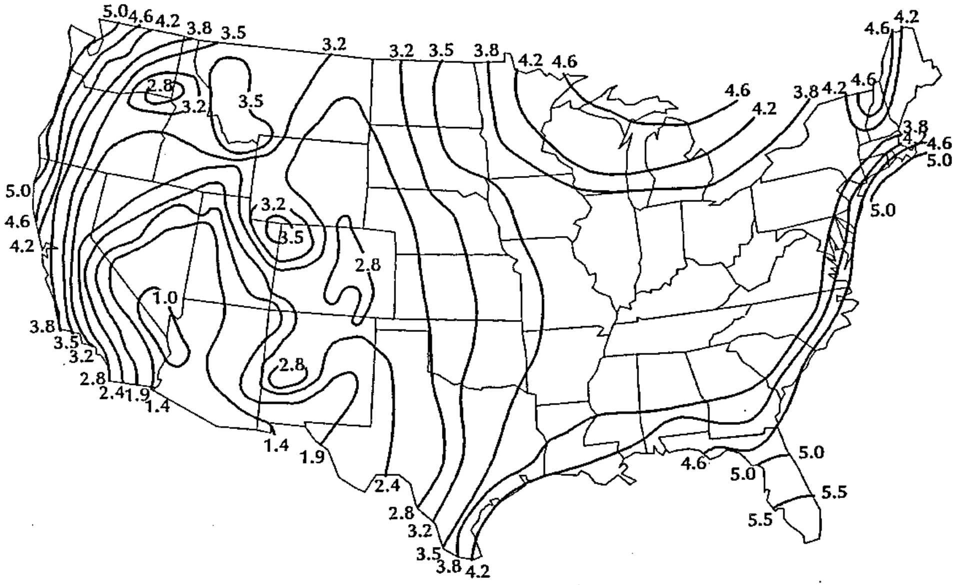
6.4 Characteristics of the Regions

Tables 6.2, 6.3, and 6.4 summarize the seasonal and annual averages of the reconstructed light extinction coefficients for each of the 19 regions in the United States, averaged over the first three years of the IMPROVE monitoring program, March 1988 through February 1991.

Table 6.2 shows the breakdown of extinction among fine and coarse particles scattering and light absorption. In addition, this table shows the percentage of total light extinction (including Rayleigh) that is caused by aerosol light extinction (both scattering and absorption).



(a) Annual mean relative humidity.



(b) F_T.

Figure 6.5. Spatial variation in average relative humidity (NOAA, 1978) and the sulfate *RH* correction factor F_T.

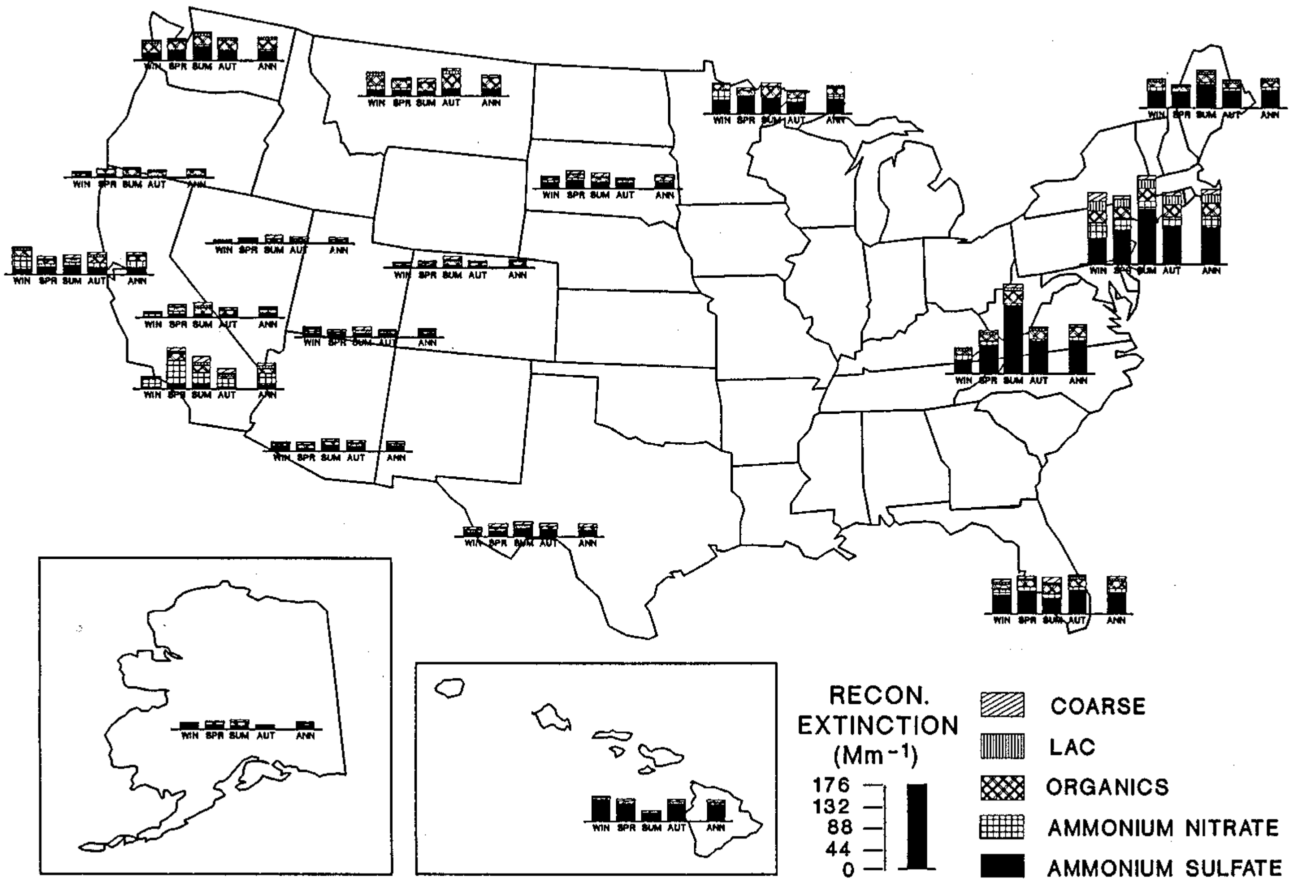


Figure 6.6. Spatial and seasonal distribution of reconstructed aerosol light extinction coefficient (Mm^{-1}) in the United States for the three-year period, March 1988 through February 1991. For each of the 19 regions, the bars show the contributions to aerosol light extinction of sulfate, nitrate, organic carbon, light absorbing carbon, and coarse particles and fine soil. From left to right the bars show winter, spring, summer, autumn, and annual averages.

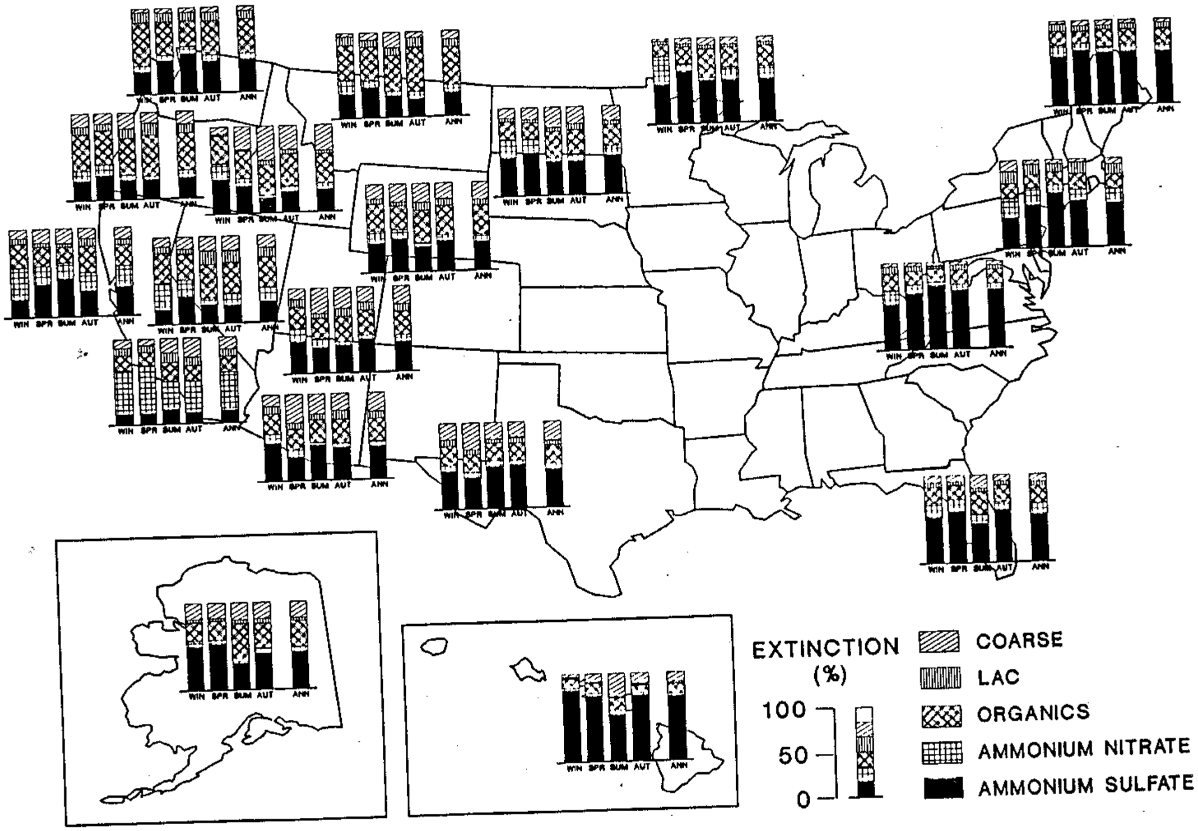


Figure 6.7. Spatial and seasonal distribution of the reconstructed light extinction budget in the United States for the three-year period, March 1988 through February 1991. For each of the 19 regions, the bars show the percentage contributions to aerosol light extinction of sulfate, nitrate, organic carbon, light absorbing carbon, and coarse particles and fine soil. From left to right the bars show winter, spring, summer, autumn, and annual averages.

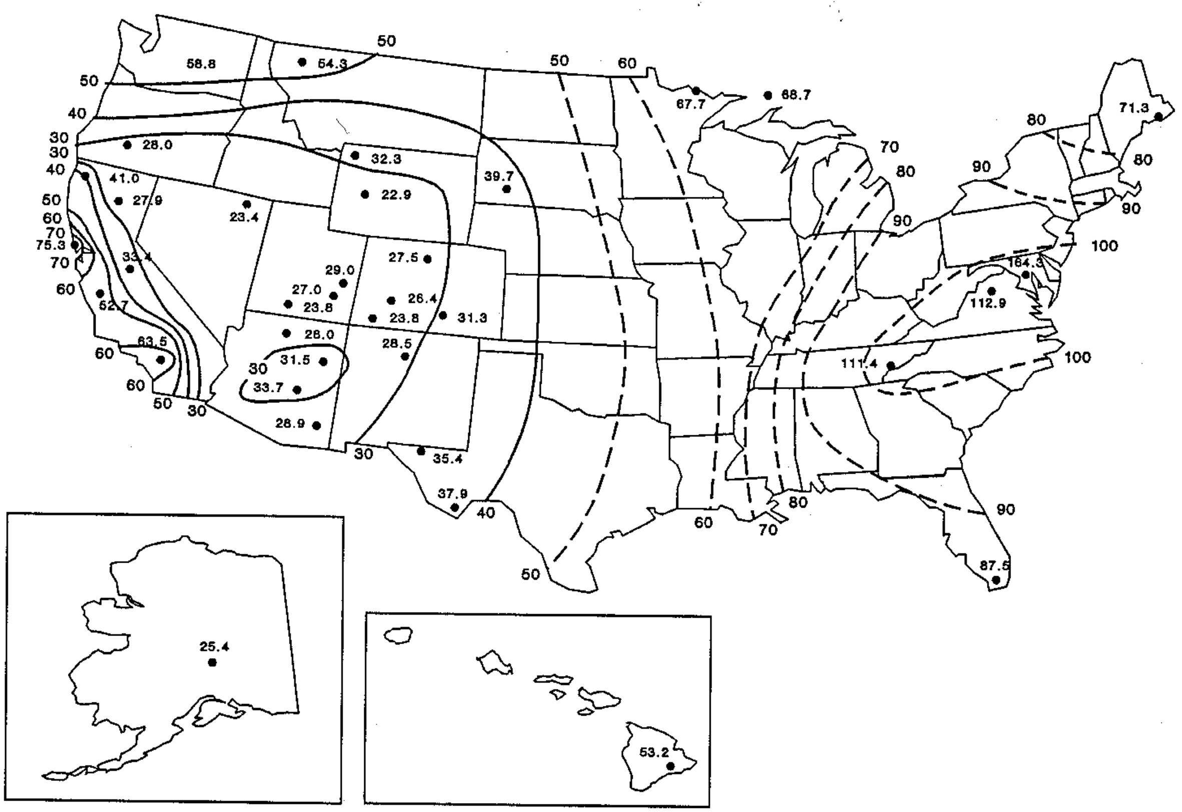


Figure 6.8. Three-year averages of total reconstructed light extinction coefficient (Mm^{-1}) for each of the sites in the IMPROVE network in the United States for the 3-year period, March 1988 through February 1991.

Also, the average relative humidity at each site is shown. Table 6.3 shows the aerosol light extinction as well as the contributions of sulfate, nitrate, organic carbon, light absorbing carbon, and coarse particles (including fine soil). Table 6.4 shows the aerosol light extinction budgets: the fractions (percent) of total aerosol (non-Rayleigh) light extinction contributed by sulfate, nitrate, organic carbon, light absorbing carbon, and coarse particles (including fine soil).

The characteristics of each region, in alphabetic order, are briefly discussed below.

Alaska. The Alaska region consists only of the measurements at Denali National Park. Here the three-year average reconstructed total light extinction coefficient was calculated to be 25 Mm^{-1}, of which aerosol extinction constituted 61 percent. There is a modest seasonal variation in total reconstructed light extinction, with highest extinction in summer and lowest in autumn. However, there is significant seasonal variation in the individual components of aerosol extinction. For example, organic carbon extinction is highest in summer (8.2 Mm^{-1}) and lowest in winter (2.8 Mm^{-1}). Nitrate is highest in winter (1.0 Mm^{-1}) and lowest in summer (0.3 Mm^{-1}). Sulfate is the largest single contributor to aerosol extinction at 43%, followed by organic carbon (30%), coarse particles and fine soil (18%), and nitrate and light absorbing carbon (at 4% each).

Appalachian Mountains. This region consists of measurements at two sites: Great Smoky Mountains and Shenandoah National Parks. The average reconstructed total light extinction coefficient in this region, averaged over the three-year period, of 112 Mm^{-1} was close to the highest measured throughout the IMPROVE network (Washington, D.C. was highest). Virtually all of the extinction (91%) was due to aerosol light extinction. There is a very strong seasonal variation in total reconstructed light extinction with a summer average of 193 Mm^{-1} and a winter average of 64 Mm^{-1}. This seasonal variation is largely due to the extreme seasonal variation in sulfate light extinction: summer sulfate extinction is nearly five times larger than extinction in winter. This can be attributed to the seasonal variation in sulfate concentrations (due to differences in photochemistry) and also to the fact that summer is the most humid season with an average relative humidity of 78%. Thus, sulfate aerosols contain much liquid water at such high humidities. Sulfate is the most dominant component of aerosol light extinction. It contributes more than two-thirds (68%), while in summer its contribution is more than three-fourths (76%). Organic carbon is the next largest contributor at 16%, followed by nitrate (7%), light absorbing carbon (5%), and coarse particles and fine soil (4%).

Boundary Waters. This region, in Minnesota, consists of two sets of measurements: in Isle Royale and Voyageurs National Parks. Over the three-year period, the average total reconstructed light extinction coefficient was 68 Mm^{-1}. There was very little seasonal variation in total light extinction; however, nitrate and organic carbon varied significantly. Nitrate extinction peaked strongly in the winter (20.9 Mm^{-1}) but was very small in summer (1.8 Mm^{-1}). Organic carbon extinction was highest in summer (21.2 Mm^{-1}) and lowest in winter (8.6 Mm^{-1}). Once again, sulfate was the dominant contributor: at 51%, sulfates contributed over half of the aerosol light extinction. Sulfate's contribution was followed by organic carbon (24%), nitrate (15%), coarse particles and fine soil (7%), and light absorbing carbon (4%).

Table 6.2 Seasonal and annual averages, averaged over the three-year period from March 1988 through February 1991, of reconstructed total light extinction coefficient (Mm^{-1}) for the 19 regions in the IMPROVE network. Also shown are the light scattering coefficients resulting from fine and coarse aerosols, light absorption for carbonaceous aerosol, percentage of total extinction resulting from aerosols, and the average region relative humidity.

Season	Total extinction	Fine scattering	Coarse scattering	Absorption	Percent aerosol	Relative humidity
ALASKA						
Winter	23.9	10.8	2.6	0.5	58	68
Spring	27.0	13.5	2.9	0.5	63	67
Summer	28.8	14.2	3.7	0.9	65	70
Autumn	21.0	8.4	2.1	0.6	52	75
ANNUAL	25.4	11.9	2.8	0.6	61	70
APPALACHIAN						
Winter	63.5	47.3	2.1	4.1	84	66
Spring	97.5	79.5	3.3	4.6	90	66
Summer	193.1	170.7	7.6	4.8	95	78
Autumn	105.8	87.3	3.7	4.9	91	73
ANNUAL	112.2	93.3	4.3	4.6	91	71
BOUNDARY WATERS						
Winter	72.1	58.0	2.1	1.9	86	79
Spring	63.3	47.9	3.5	1.9	84	75
Summer	72.6	54.6	5.4	2.6	86	82
Autumn	58.6	42.9	3.7	2.0	83	84
ANNUAL	68.2	52.3	3.8	2.2	85	80
CASCADES						
Winter	50.5	34.1	1.9	4.6	80	89
Spring	54.9	38.2	2.2	4.5	82	77
Summer	68.1	49.6	3.1	5.4	85	74
Autumn	57.0	39.4	2.5	5.1	82	80
ANNUAL	58.8	41.6	2.4	4.9	83	80
COLORADO PLATEAU						
Winter	28.8	14.8	2.2	1.9	63	58
Spring	24.5	9.3	4.3	0.9	59	40
Summer	29.2	12.8	4.7	1.8	65	39
Autumn	25.9	11.5	2.7	1.6	61	46
ANNUAL	27.1	12.1	3.5	1.5	63	46
CENTRAL ROCKIES						
Winter	22.7	9.8	2.1	0.8	55	63
Spring	27.4	13.0	3.6	0.7	63	58
Summer	34.9	17.2	5.4	2.3	70	53
Autumn	26.4	12.2	2.9	1.3	62	57

ANNUAL	28.1	13.2	3.6	1.3	64	58

Table 6.2 Continued.

Season	Total extinction	Fine scattering	Coarse scattering	Absorption	Percent aerosol	Relative humidity
CENTRAL COAST						
Winter	67.8	49.4	4.8	3.6	82	73
Spring	48.9	31.2	5.9	1.9	79	68
Summer	50.8	32.7	6.7	1.4	80	65
Autumn	56.2	37.3	4.9	4.0	82	67
ANNUAL	56.3	38.1	5.6	2.7	81	68
FLORIDA						
Winter	80.4	61.3	5.3	3.8	88	82
Spring	87.3	68.9	5.5	2.9	89	75
Summer	84.6	60.6	10.9	3.1	88	80
Autumn	90.2	70.3	5.6	4.3	89	83
ANNUAL	87.5	67.3	6.7	3.6	89	80
GREAT BASIN						
Winter	18.7	7.8	0.8	0.2	47	73
Spring	21.5	8.2	3.1	0.3	54	55
Summer	27.1	9.4	6.8	1.0	63	38
Autumn	24.5	9.6	4	0.8	59	55
ANNUAL	23.4	8.8	4	0.6	57	55
HAWAII						
Winter	62.3	49.4	1.9	1.0	84	80
Spring	55.9	40.7	4.6	0.7	82	80
Summer	33.4	16.7	6.3	0.4	70	80
Autumn	55.6	39.2	5.7	0.7	82	80
ANNUAL	53.2	37.5	5.1	0.7	81	80
NORTHEAST						
Winter	70.2	53.4	2.1	4.7	86	70
Spring	59.0	43.1	2.7	3.2	83	65
Summer	87.9	69.4	4.3	4.2	89	72
Autumn	67.3	51.0	2.7	3.7	85	75
ANNUAL	71.3	54.4	2.9	4.0	86	70
NORTHERN GREAT PLAINS						
Winter	37.4	23.4	2.8	1.2	73	70
Spring	45.3	29.5	4.6	1.2	78	64
Summer	42.1	23.2	7.1	1.8	76	58
Autumn	33.7	17.8	4.4	1.4	70	61
ANNUAL	39.7	23.6	4.7	1.4	75	63
NORTHERN ROCKIES						
Winter	60.1	43.4	1.7	5.0	83	82
Spring	48.5	32.3	3.1	3.1	79	77
Summer	46.4	26.5	6.6	3.3	78	68
Autumn	66	45.7	4.0	6.3	85	79

ANNUAL	54.3	36	3.9	4.3	82	76

Table 6.2 Continued

Season	Total extinction	Fine scattering	Coarse scattering	Absorption	Percent aerosol	Relative humidity
SOUTHERN CALIFORNIA						
Winter	37.5	22.1	3.0	2.4	73	47
Spring	94.7	71.9	7.1	5.8	89	54
Summer	76	47.3	10.9	7.8	87	44
Autumn	50.6	27.1	9.4	4.1	80	40
ANNUAL	63.5	41.2	7.5	4.8	84	46
SONORA						
Winter	28.9	14.8	2.4	1.7	65	53
Spring	28.4	11.1	6.0	1.3	64	35
Summer	36.1	18.5	5.8	1.8	72	41
Autumn	31.7	15	4.3	2.4	68	42
ANNUAL	31.3	14.9	4.5	1.8	68	43
SIERRA						
Winter	23.7	11.2	1.5	1.0	58	50
Spring	36.6	21.2	3.7	1.7	73	62
Summer	40.6	20.8	5.1	4.8	75	42
Autumn	31.7	15.2	3.7	2.8	68	43
ANNUAL	33.4	17.5	3.4	2.5	70	49
SIERRA/HUMBOLDT						
Winter	22.7	9.6	2.0	1.1	56	70
Spring	29.3	15.6	2.3	1.4	66	67
Summer	32.3	15.7	4.0	2.6	69	56
Autumn	25.4	11.4	2.0	2.0	61	60
ANNUAL	28.0	13.5	2.7	1.8	64	63
WASHINGTON DC						
Winter	158.4	109.6	18.7	20.2	94	66
Spring	151.0	117.0	7.1	17.0	93	66
Summer	192.2	156.9	9.0	16.3	95	78
Autumn	157.3	121.9	5.8	19.6	94	73
ANNUAL	164.3	125.3	10.6	18.4	94	71
WEST TEXAS						
Winter	29.4	14.3	3.7	1.4	66	50
Spring	37.3	17.4	8.4	1.6	73	39
Summer	41.9	24.2	6.3	1.3	76	53
Autumn	37.9	21.2	5.0	1.7	73	54
ANNUAL	36.7	19.3	5.9	1.5	73	49

Table 6.3 Seasonal and annual averages, averaged over the three-year period from March 1988 through February 1991, of reconstructed aerosol light extinction coefficient (Mm^{-1}) for the 19 regions in the IMPROVE network. Also shown are the light extinction coefficients (Mm^{-1}) resulting from sulfate, nitrate, organic carbon, light absorbing carbon, and coarse particles/fine soil.

Season	Aerosol extinction	Sulfate	Nitrate	Organics	Elemental carbon	Soil and coarse
ALASKA						
Winter	13.9	6.9	1.0	2.8	0.5	2.6
Spring	17.0	9.1	0.7	3.8	0.5	2.9
Summer	18.8	5.6	0.3	8.2	0.9	3.7
Autumn	11.0	4.6	0.6	3.2	0.6	2.1
ANNUAL	15.4	6.7	0.7	4.6	0.6	2.8
APPALACHIAN						
Winter	53.5	28.8	8.1	10.5	4.1	2.1
Spring	87.5	57.8	8.1	13.6	4.6	3.3
Summer	183.1	138.4	4.3	27.9	4.8	7.6
Autumn	95.8	65.7	5.6	16.0	4.9	3.7
Annual	102.2	69.7	6.9	16.7	4.6	4.3
BOUNDARY WATERS						
Winter	62.1	28.5	20.9	8.6	1.9	2.1
Spring	53.3	32.6	4.5	10.8	1.9	3.5
Summer	62.6	31.5	1.8	21.2	2.6	5.4
Autumn	48.6	24.9	6.8	11.3	2.0	3.7
Annual	58.2	29.8	8.4	14.1	2.2	3.8
CASCADES						
Winter	40.5	11.0	2.7	20.4	4.6	1.9
Spring	44.9	17.7	3.1	17.3	4.5	2.2
Summer	58.1	27.4	4.7	17.5	5.4	3.1
Autumn	47.0	18.1	2.7	18.6	5.1	2.5
ANNUAL	48.8	19.0	3.3	19.2	4.9	2.4
COLORADO PLATEAU						
Winter	18.8	6.7	3.3	4.7	1.9	2.2
Spring	14.5	4.5	1.1	3.6	0.9	4.3
Summer	19.2	6.2	0.8	5.7	1.8	4.7
Autumn	15.9	6.2	0.8	4.6	1.6	2.7
Annual	17.1	6.0	1.4	4.7	1.5	3.5
CENTRAL ROCKIES						
Winter	12.7	4.2	1.7	3.9	0.8	2.1
Spring	17.4	6.6	1.9	4.6	0.7	3.6
Summer	24.9	6.5	0.9	9.7	2.3	5.4
Autumn	16.4	5.8	0.9	5.5	1.3	2.9

ANNUAL	18.1	5.8	1.3	6.1	1.3	3.6

Table 6.3 Continued

Season	Aerosol extinction	Sulfate	Nitrate	Organics	Elemental carbon	Soil and coarse
CENTRAL COAST						
Winter	57.8	11.4	25.0	13.0	3.6	4.8
Spring	38.9	14.7	8.4	8.1	1.9	5.9
Summer	40.8	18.6	7.0	7.0	1.4	6.7
Autumn	46.2	14.3	9.8	13.1	4.0	4.9
ANNUAL	46.3	15.4	12.1	10.6	2.7	5.6
FLORIDA						
Winter	70.4	37.9	10.9	12.5	3.8	5.3
Spring	77.3	45.6	10.5	12.8	2.9	5.5
Summer	74.6	33.5	7.2	19.8	3.1	10.9
Autumn	80.2	47.6	8.1	14.6	4.3	5.6
ANNUAL	77.5	42.4	9.5	15.4	3.6	6.7
GREAT BASIN						
Winter	8.7	3.4	1.6	2.8	0.2	0.8
Spring	11.5	3.6	1.0	3.6	0.3	3.1
Summer	17.1	2.9	0.5	6.0	1.0	6.8
Autumn	14.5	3.5	0.9	5.2	0.8	4.0
ANNUAL	13.4	3.4	0.9	4.6	0.6	4.0
HAWAII						
Winter	52.3	42.6	1.0	5.8	1.0	1.9
Spring	45.9	34.2	1.1	5.3	0.7	4.6
Summer	23.4	12.3	1.2	3.2	0.4	6.3
Autumn	45.6	33.9	0.7	4.5	0.7	5.7
ANNUAL	43.2	31.5	1.0	5.0	0.7	5.1
NORTHEAST						
Winter	60.2	35.4	8.0	10.0	4.7	2.1
Spring	49.0	31.9	3.9	7.3	3.2	2.7
Summer	77.9	48.9	3.8	16.8	4.2	4.3
Autumn	57.3	36.3	4.8	9.9	3.7	2.7
ANNUAL	61.3	38.3	5.1	11.0	4.0	2.9
NORTHERN GREAT PLAINS						
Winter	27.4	11.9	5.7	5.7	1.2	2.8
Spring	35.3	17.5	5.4	6.6	1.2	4.6
Summer	32.1	12.7	1.1	9.4	1.8	7.1
Autumn	23.7	9.4	1.6	6.7	1.4	4.4
ANNUAL	29.7	13.1	3.3	7.3	1.4	4.7
NORTHERN ROCKIES						
Winter	50.1	14.4	8.2	20.8	5.0	1.7
Spring	38.5	14.0	3.1	15.2	3.1	3.1
Summer	36.4	9.2	1.7	15.6	3.3	6.6

Autumn	56.0	12.3	4.1	29.3	6.3	4.0
ANNUAL	44.3	12.4	4.0	19.6	4.3	3.9

Table 6.3 Continued

Season	Aerosol extinction	Sulfate	Nitrate	Organics	Elemental carbon	Soil and coarse
SOUTHERN CALIFORNIA						
Winter	27.5	3.3	13.9	4.9	2.4	3.0
Spring	84.7	11.3	47.2	13.3	5.8	7.1
Summer	66.0	11.1	21.5	14.7	7.8	10.9
Autumn	40.6	5.2	14.9	7.0	4.1	9.4
ANNUAL	53.5	7.7	23.8	9.7	4.8	7.5
SONORA						
Winter	18.9	8.1	2.0	4.6	1.7	2.4
Spring	18.4	5.1	1.4	4.6	1.3	6.0
Summer	26.1	10.7	1.0	6.7	1.8	5.8
Autumn	21.7	8.0	0.9	6.1	2.4	4.3
ANNUAL	21.3	8.1	1.3	5.5	1.8	4.5
SIERRA						
Winter	13.7	2.3	4.2	4.7	1.0	1.5
Spring	26.6	8.4	5.0	7.8	1.7	3.7
Summer	30.6	6.8	2.3	11.7	4.8	5.1
Autumn	21.7	4.6	2.9	7.7	2.8	3.7
ANNUAL	23.4	5.7	3.6	8.1	2.5	3.4
SIERRA/HUMBOLDT						
Winter	12.7	2.8	1.4	5.3	1.1	2.0
Spring	19.3	5.5	2.3	7.7	1.4	2.3
Summer	22.3	5.1	1.3	9.4	2.6	4.0
Autumn	15.4	3.4	0.8	7.2	2.0	2.0
ANNUAL	18.0	4.4	1.4	7.7	1.8	2.7
WASHINGTON DC						
Winter	148.4	51.9	32.7	25.0	20.2	18.7
Spring	141.0	70.5	25.0	21.5	17.0	7.1
Summer	182.2	112.9	16.3	27.8	16.3	9.0
Autumn	147.3	77.6	18.8	25.6	19.6	5.8
ANNUAL	154.3	75.6	24.6	25.0	18.4	10.6
WEST TEXAS						
Winter	19.4	8.6	1.3	4.4	1.4	3.7
Spring	27.3	10.0	1.4	5.9	1.6	8.4
Summer	31.9	15.6	1.9	6.7	1.3	6.3
Autumn	27.9	14.5	1.0	5.6	1.7	5.0
ANNUAL	26.7	12.2	1.4	5.7	1.5	5.9

Table 6.4 Seasonal and annual averages, averaged over the three-year period from March 1988 through February 1991, of percentage contributions to the reconstructed aerosol light extinction coefficient (light extinction budget) for the 19 regions in the IMPROVE network for sulfate, nitrate, organic carbon, light absorbing carbon, and coarse particles/fine soil.

Season	Sulfate	Nitrate	Organics	Elemental carbon	Soil and Coarse
ALASKA					
Winter	49.7	7.3	20.4	3.9	18.7
Spring	53.3	4.1	22.0	3.2	17.3
Summer	30.0	1.8	44.0	4.6	19.6
Autumn	41.5	5.6	28.8	5.4	18.7
ANNUAL	43.3	4.4	29.8	4.1	18.4
APPALACHIAN					
Winter	53.8	15.1	19.6	7.6	3.9
Spring	66.1	9.2	15.6	5.3	3.8
Summer	75.6	2.3	15.3	2.6	4.2
Autumn	68.6	5.8	16.7	5.1	3.8
ANNUAL	68.3	6.7	16.3	4.5	4.2
BOUNDARY WATERS					
Winter	46.2	33.0	14.1	3.2	3.4
Spring	60.9	8.6	20.2	3.6	6.6
Summer	50.4	2.9	33.9	4.2	8.6
Autumn	51.4	13.6	23.3	4	7.6
ANNUAL	51.1	14.5	24.2	3.7	6.5
CASCADES					
Winter	27.1	6.6	50.4	11.3	4.6
Spring	39.5	6.9	38.6	10.1	4.9
Summer	47.2	8.0	30.1	9.4	5.3
Autumn	38.4	5.7	39.6	10.9	5.4
ANNUAL	39.0	6.8	39.4	10.0	4.8
COLORADO PLATEAU					
Winter	37.7	14.8	25.5	9.5	12.4
Spring	31.5	7.9	25.1	6.0	29.5
Summer	32.3	4.4	29.9	8.9	24.4
Autumn	39.1	5.0	28.9	9.8	17.3
ANNUAL	35.3	7.9	27.6	8.6	20.5
CENTRAL ROCKIES					
Winter	33.8	13.1	31.0	6.0	16.1
Spring	38.2	10.6	26.6	4.2	20.4
Summer	28.5	3.8	37.4	8.9	21.3

Autumn	35.3	5.6	33.8	7.6	17.7
ANNUAL	32.7	7.3	33.6	7.1	19.3

Table 6.4 Continued

Season	Sulfate	Nitrate	Organics	Elemental carbon	Soil and coarse
CENTRAL COAST					
Winter	21.5	35.6	26.9	6.8	9.3
Spring	37.4	20.9	21.7	4.9	15.1
Summer	44.2	17.2	18.2	4.0	16.4
Autumn	30.0	19.7	30.3	9.3	10.7
ANNUAL	33.0	24.0	24.5	6.2	12.2
FLORIDA					
Winter	53.8	15.5	17.7	5.4	7.5
Spring	59.0	13.6	16.6	3.7	7.1
Summer	44.9	9.7	26.5	4.2	14.6
Autumn	59.4	10.1	18.2	5.3	7.0
Annual	54.6	12.2	19.8	4.6	8.6
GREAT BASIN					
Winter	38.8	18.5	32.3	1.8	8.7
Spring	31.3	8.4	31.4	2.4	26.6
Summer	16.9	2.8	34.8	5.7	39.7
Autumn	24.4	6.4	35.9	5.7	27.7
ANNUAL	25.3	6.5	34.1	4.1	29.9
HAWAII					
Winter	81.5	1.8	11.2	1.8	3.6
Spring	74.4	2.5	11.6	1.4	10.1
Summer	52.8	5.0	13.7	1.8	26.8
Autumn	74.5	1.6	9.9	1.5	12.5
ANNUAL	72.8	2.4	11.6	1.6	11.7
NORTHEAST					
Winter	58.8	13.3	16.7	7.8	3.4
Spring	65.0	7.9	14.9	6.6	5.6
Summer	62.7	4.8	21.5	5.4	5.5
Autumn	63.3	8.4	17.2	6.4	4.7
ANNUAL	62.4	8.4	17.9	6.5	4.8
NORTHERN GREAT PLAINS					
Winter	43.5	21.0	20.8	4.5	10.2
Spring	49.6	15.2	18.8	3.4	13.1
Summer	39.4	3.5	29.4	5.6	22.1
Autumn	39.9	6.9	28.4	6.1	18.7
ANNUAL	44.0	11.0	24.5	4.8	15.8
NORTHERN ROCKIES					
Winter	28.8	16.3	41.5	9.9	3.5
Spring	36.3	8.1	39.4	8.1	8.1

Summer	25.4	4.7	42.7	9.2	18.0
Autumn	21.9	7.4	52.3	11.2	7.2
ANNUAL	28.0	9.0	44.3	9.8	8.9

Table 6.4 Continued

Season	Sulfate	Nitrate	Organics	Elemental carbon	Soil and coarse
SOUTHERN CALIFORNIA					
Winter	12.0	50.6	17.8	8.8	10.8
Spring	13.3	55.7	15.7	6.8	8.4
Summer	16.8	32.5	22.3	11.8	16.5
Autumn	12.7	36.7	17.3	10.1	23.2
ANNUAL	14.4	44.4	18.2	9.0	13.9
SONORA					
Winter	44.6	9.7	24.4	8.8	12.5
Spring	28.0	7.3	25	7.0	32.8
Summer	40.8	4.0	25.7	7.0	22.5
Autumn	38.4	3.8	27.8	10.8	19.2
ANNUAL	38.8	5.9	25.7	8.4	21.1
SIERRA					
Winter	16.9	30.9	34.1	7.5	10.6
Spring	31.7	18.8	29.3	6.5	13.8
Summer	22.1	7.6	38.1	15.6	16.6
Autumn	21.0	13.4	35.6	13.0	16.9
ANNUAL	24.5	15.3	34.8	10.8	14.6
SIERRA/HUMBOLDT					
Winter	22.1	11.1	42.3	9.0	15.5
Spring	28.6	12.2	39.7	7.3	12.2
Summer	22.7	5.7	42.0	11.8	17.8
Autumn	22.1	4.9	46.9	13.1	13.0
ANNUAL	24.4	7.9	42.8	10.1	14.9
WASHINGTON DC					
Winter	34.9	22.0	16.9	13.6	12.6
Spring	50.0	17.7	15.2	12.0	5.0
Summer	62.0	8.9	15.2	8.9	4.9
Autumn	52.7	12.8	17.4	13.3	3.9
ANNUAL	49.0	16.0	16.2	11.9	6.9
WEST TEXAS					
Winter	44.2	6.8	22.7	7.0	19.3
Spring	36.6	5.1	21.6	5.8	30.9
Summer	49.0	6.0	21.1	4.1	19.8
Autumn	51.3	3.8	20.5	6.1	18.3
ANNUAL	45.5	5.4	21.4	5.6	22.2

Cascade Mountains. This region in Washington State consists of only the measurements at Mount Rainier National Park, southeast of Seattle. Here the three-year average reconstructed light extinction was 59 Mm^{-1}. There was a modest seasonality, with summer extinction being the largest and winter the lowest. Most of this seasonality is from sulfate light extinction which varies from 11 Mm^{-1} in summer to 27.4 Mm^{-1} in summer. At Mount Rainier sulfate and organic carbon contribute equally (each at 39% of the aerosol extinction). Together they account for over two-thirds of the aerosol extinction. Their contributions are followed by light absorbing carbon (10%), nitrate (7%), and coarse particles and fine soil (5%).

Central Rocky Mountains. The measurements in this region are made at five locations in the mountainous Class I areas of Colorado and Wyoming, including the Bridger and Weminuche wilderness areas, Rocky Mountain and Yellowstone National Parks, and Great Sand Dunes National Monument. The three-year average reconstructed total light extinction was fairly low at; 28 Mm^{-1}. Summer extinction is much higher than winter extinction. Although all the aerosol components, except nitrate, vary by season similarly, the greatest seasonal variation appears to be in the organic carbon and the light absorbing carbon contributions. As in the Cascades, organic carbon and sulfate are nearly equal contributors to light extinction at about one-third each (34%, 33%). Their contribution is followed by coarse particles and fine soil (19%) and light absorbing carbon and nitrate (at 7% each).

Coastal Mountains. This region includes three Class I areas along and near the coast of Northern California: Pinnacles National Monument, Point Reyes National Seashore, and Redwoods National Park. This region has an average reconstructed light extinction of 56 Mm^{-1}, twice that for the Central Rockies. Unlike most other regions, extinction is highest in winter and lowest in summer. Most of this seasonal variation is caused by the nitrate, organic carbon, and light absorbing carbon components, which all have peaks in winter. Perhaps the winter peaks for the carbon species are related to wintertime home heating with wood. The sulfate and coarse particle and fine soil components vary seasonally, with maxima in summer and minima in winter. The nitrate seasonality is strongest, in winter nitrate extinction averages 25 Mm^{-1}, while in summer it is only 7 Mm^{-1}. On average, sulfate contributes one-third of aerosol light extinction (33%), nitrate and organic carbon each one-quarter (24% each), followed by coarse particles and fine soil (12%), and light absorbing carbon (6%).

Colorado Plateau. This region in the Four Corners states of the Southwest is the most intensively monitored in the IMPROVE network. There are seven sites, most of them within the so-called Golden Circle of national parks: Arches, Bandelier, Bryce Canyon, Canyonlands, Grand Canyon, Mesa Verde, and Petrified Forest National Parks. The three-year average total reconstructed light extinction coefficient was relatively low for this region: 27 Mm^{-1}. There is very little seasonal variation in reconstructed light extinction; however, nitrate extinction is considerably higher in winter than in summer (3.3 Mm^{-1} versus 0.8 Mm^{-1}). Here the largest single contributor to aerosol light extinction is sulfate (35%), followed by organic carbon (28%), coarse particles and fine soil (21%), light absorbing carbon (9%), and nitrate (8%).

Florida. This region consists of only one site, Everglades National Park. At Everglades the total reconstructed light extinction coefficient averaged 88 Mm^{-1} over the first three years of

IMPROVE. There is not much seasonal variation in light extinction there. Sulfate was, by far, the largest contributor to aerosol light extinction (55%), followed by organic carbon (20%), nitrate (12%), coarse particles and fine soil (9%), and light absorbing carbon (5%).

Great Basin. The Great Basin of Nevada was represented by only one set of measurements at Jarbidge Wilderness Area in northeastern Nevada. Here the three-year average total reconstructed light extinction coefficient was the lowest of any of the regions in the United States (even lower than Alaska). It was 23 Mm^{-1}, only 13 Mm^{-1} above the Rayleigh scattering coefficient. There is significant seasonal variability in extinction at this site, with highest extinction in summer and lowest extinction in winter. Most of this seasonal variation is due to the seasonal variations in organic carbon, light absorbing carbon, and coarse particles and fine soil. Sulfate and nitrate extinction actually was highest in winter and lowest in summer. Organic carbon contributed about one-third (34%) of aerosol extinction, while coarse particles/fine soil was 29% and sulfate was 25%. These contributions were followed distantly by nitrate (7%), and light absorbing carbon (4%).

Hawaii. The Hawaiian Islands were represented by a single measurement site at Hawaii Volcanoes National Park. The total reconstructed light extinction coefficient averaged 53 Mm^{-1}. There was a significant seasonal variation, with winter aerosol extinction more than twice that during the summer. This seasonality is contributed largely by the seasonal variations in sulfate extinction, by far, the largest contributor to light extinction. Sulfate extinction was nearly three-fourths (73%) of aerosol light extinction. Other contributions were relatively small: organic carbon (12%), coarse particles and fine soil (12%), nitrate (2%), and light absorbing carbon (2%).

Northeast. The northeastern United States is represented by the set of measurements at Acadia National Park on the coast of Maine. At Acadia the total reconstructed light extinction coefficient averaged 71 Mm^{-1}, with highest extinction in summer and lowest in autumn. Sulfate and organic carbon extinction were highest in summer and lowest in spring. Nitrate and light absorbing carbon extinction were highest in winter. Sulfate was the largest contributor to aerosol light extinction (62%), followed by organic carbon (18%), nitrate (8%), light absorbing carbon (7%), and coarse particles and fine soil (5%).

Northern Great Plains. Only one set of aerosol measurements was made in this region, at Badlands National Monument in South Dakota, where reconstructed light extinction averaged 40 Mm^{-1}. Unlike any other region, extinction was highest in spring and lowest in autumn. This seasonality was due primarily to the sulfate and nitrate components. Organic carbon and light absorbing carbon extinction were both maximum in summer and minimum in winter. Again, sulfate was the dominant component of aerosol light extinction, contributing 44%, followed by organic carbon (25%), coarse particles and fine soil (16%), nitrate (11%), and light absorbing carbon (5%).

Northern Rocky Mountains. This region consisted of the measurements made at Glacier National Park in Montana, close to the Canadian border, where the total reconstructed light extinction coefficient averaged 54 Mm^{-1}. Autumn extinction was highest, and summer extinction was lowest. This seasonal variation was due primarily to the effects of organic carbon and light absorbing carbon, which both had maximum extinction in autumn. Both sulfate and nitrate extinction had maxima in winter and minima in summer. Coarse particle and fine soil extinction were maximum in summer and minimum in winter. Organic carbon was the largest single contributor to aerosol light extinction in Glacier (44%). Its contribution was followed by sulfate (28%), light absorbing carbon (10%), nitrate (9%), and coarse particles and fine soil (9%).

Sierra Nevada. The aerosol in the Sierra Nevada mountains in California were monitored at Yosemite National Park. The reconstructed total light extinction averaged 33 Mm^{-1}, with strong seasonal variation resulting in a summer average of 41 Mm^{-1} and a winter average of 24 Mm^{-1}. This seasonality is due primarily to the strong seasonal variation in extinction due to organic carbon, light absorbing carbon, and coarse particles/fine soil. Organic carbon was the largest single contributor to aerosol extinction (35%), followed by sulfate (25%), nitrate (15%), coarse particles/fine soil (15%), and light absorbing carbon (11%).

Sierra-Humboldt. The region further north in the Sierra Nevada and Humboldt mountain ranges was measured at Crater Lake National Park in Oregon and Lassen Volcanoes National Park in Northern California. For this region, total reconstructed light extinction averaged 28 Mm^{-1}, with maximum extinction in summer and minimum extinction in winter. This seasonality was due primarily to the variations in extinction caused by organic carbon, light absorbing carbon, and coarse particles/fine soil. Organic carbon was, by far, the largest contributor to aerosol light extinction (43%), followed by sulfate (24%), coarse particles and fine soil (15%), light absorbing carbon (10%), and nitrate (8%).

Sonoran Desert. This region in southeastern Arizona was monitored at two sites: Chiracahua and Tonto National Monuments. The three-year average total reconstructed light extinction coefficient was 31 Mm^{-1}. There was minimal seasonal variation in extinction; however, extinction was highest in summer and lowest in spring. Sulfate extinction varied from a high of 10.7 Mm^{-1} in summer to a low of 5.1 Mm^{-1} in spring. Organic carbon extinction also varied from a summer high of 6.7 Mm^{-1} to a spring low of 4.6 Mm^{-1}. Fine soil and coarse particle extinction was highest in spring when it was the largest single contributor to light extinction. In this region sulfate was the largest contributor to aerosol light extinction at 39%, followed by organic carbon (26%), coarse particles and fine soil (21%), light absorbing carbon (8%), and nitrate (6%).

Southern California. Measurements in this region were made in San Gorgonio National Monument, east of the Los Angeles metropolitan area. Total reconstructed light extinction averaged 64 Mm^{-1}. The maximum extinction occurred in spring and the minimum occurred in winter. This seasonal variation was caused largely by the seasonal variation in nitrate, and to a lesser extent by sulfate. Extinction caused by organic carbon, light absorbing carbon, and coarse particles/fine soil all peaked in summer and had minima in winter. Unlike any other region in the IMPROVE network, nitrate was the largest single component of aerosol light extinction. Nitrate contributed 44%, organic carbon 18%, sulfate 14%, coarse particles/fine soil 14%, and light absorbing carbon 9%.

Washington, D.C. The highest light extinction coefficient, reconstructed from aerosol concentration, was found in Washington. It averaged 164 Mm^{-1} over the three-year period of

IMPROVE. Extinction was somewhat higher in summer (192 Mm^{-1}) and lower in spring (151 Mm^{-1}). Sulfate extinction was considerably larger in summer (113 Mm^{-1}) than in the other seasons. Organic carbon's contribution was constant over the seasons. Nitrate extinction in winter was twice what it was in summer. Sulfate was the dominant contributor to aerosol light extinction, contributing nearly half (49%), followed by nitrate and organic carbon each contributing 16%, light absorbing carbon (12%), and coarse particles and fine soil (7%).

West Texas. Total light extinction reconstructed from the aerosol measurements at Big Bend and Guadalupe Mountains National Parks averaged 37 Mm^{-1}. Highest extinction occurred in summer and lowest extinction occurred in winter. This seasonality was contributed primarily by sulfate, which was by far the largest contributor to aerosol light extinction (46%). Sulfate's contribution was followed distantly by coarse particles and fine soil (22%), organic carbon (21%), light absorbing carbon (6%), and nitrate (5%).

It is interesting to compare the light extinction budgets to the fine aerosol budgets. Organic carbon was the largest single contributor to fine aerosol mass in nine of the 19 regions and was tied with sulfate in three regions, and sulfate was the largest single contributor to fine aerosol mass in six regions. However, sulfate has a larger light extinction efficiency than organic carbon because of its hygroscopic nature; therefore, sulfate is generally the largest single contributor to light extinction, being the largest contributor in 12 of 19 regions and tied with organic carbon in two additional regions (Cascades and Central Rockies). Organic carbon is the largest single contributor to aerosol light extinction in four regions: Great Basin, North Rockies, Sierra Nevada, and Sierra-Humboldt. Only in Southern California is nitrate the largest contributor. In general, then, sulfate is the dominant contributor to light extinction, followed by organic carbon, and more distantly by nitrate and fine soil/coarse particles, and finally, light absorbing carbon.

6.5 Spatial Trends in Reconstructed Light Extinction in the United States

Figure 6.9 shows the sulfate light extinction coefficient averaged over the first three years of IMPROVE (March 1988 - February 1991). Note that the highest sulfate extinction occurs in the eastern United States, and the lowest sulfate extinction occurs in Oregon, Nevada, Idaho, and Wyoming. The major gradient in sulfate light extinction is from the eastern United States to the non-urban West. However, there is also a gradient from the San Francisco Bay Area and from the Pacific Northwest to the non-urban West. Sulfate extinction is more than half of total aerosol light extinction in the eastern and north central U.S. In the Appalachians, Middle Atlantic states, and the Northeast, sulfate contributes about two-thirds of aerosol light extinction. In the worst season for sulfate (summer), sulfate's share is even higher, reaching three-quarters in the eastern United States.

Figure 6.10 shows the nitrate light extinction. There is a gradient from the east to west, with relatively high nitrate contributions in the Washington, D.C. area. However, the strongest gradient is from the urban areas of California, especially the Los Angeles metropolitan area, to the California desert. Nitrate contributions to aerosol light extinction are generally less than 10 percent, except in California, where nitrate can contribute as much as 44 percent.

Figure 6.11 shows isopleths of the organic carbon light extinction throughout the United States, averaged over the first three years of IMPROVE. Note that extinction caused by organic carbon is largest in the eastern United States and in the Pacific Northwest, and lowest in the Golden Circle of parks in southern Utah and northern Arizona. The fraction of aerosol light extinction contributed by organic carbon ranges from a high of more than 40 percent in the Pacific Northwest to less than 20 percent in the urban areas of California and in much of the eastern United States. The reason that organic carbon is a smaller share of aerosol extinction in the East is the much larger contribution of sulfate extinction there.

Figure 6.12 shows isopleths of the extinction caused by light absorbing carbon. Light absorbing carbon extinction is highest in the Pacific Northwest and in the eastern United States and lowest in the non-urban West. Light absorbing carbon contributes about 10 percent of aerosol light extinction in Northern California, the Pacific Northwest, and in Washington, D.C.; however, in most areas its contribution is much less.

6.6 Spatial Trends in Visibility in the United States

To show the effect on visibility of aerosol extinction the deciview (dv) scale is applied to the total (Rayleigh included) aerosol extinction (see Chapter 1). By utilizing the dv scale the effect of aerosol extinction on the human visual system is portrayed as a linear scale of visibility degradation. Pristine or Rayleigh conditions have a dv of zero. A one or two dv change is usually associated with the minimal or just noticeable change (JNC) in visibility perceived by the average individual.

Figure 6.13 shows isopleths of deciviews averaged over the first three years of IMPROVE. The smallest dv or best visibility is reported at Bridger Wilderness with 8.3 dv's. There is a broad region that includes the Great Basin, most of the Colorado Plateau and portions of the Central Rockies that has visibility impairment of less than 10 dv. Moving in any direction from this region generally results in a gradient of increasing dv. West of the Sierra Range and including Southern California are dv values in excess of 15 and a maximal value of 20.2 dv at Point Reyes. The northwest U.S. and all of the eastern half of the U.S. have in excess of 15 dv of impaired visibility and the region east of the Mississippi and south of the Great Lakes have impairment in excess of 20 dv with the Appalachian region exceeding 24 dv. The highest annual dv is reported at Washington D.C. with an impairment of 28 dv.

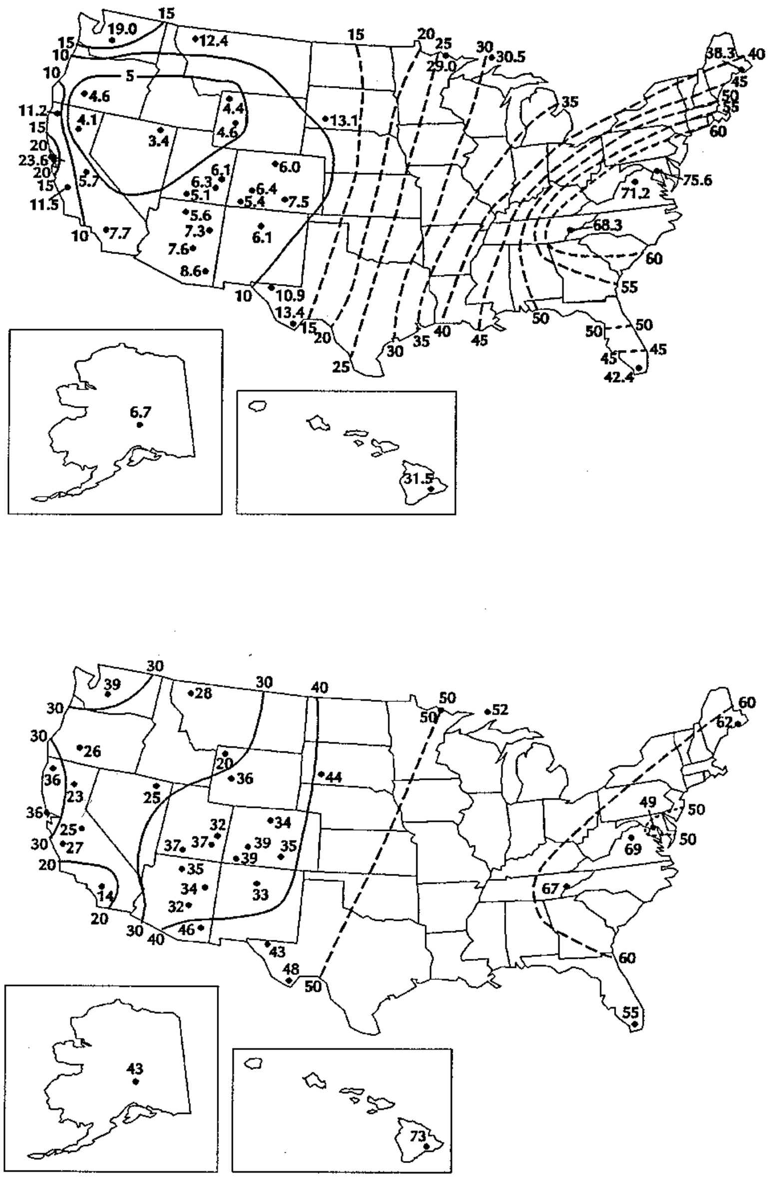


Figure 6.9. Three-year averages of reconstructed sulfate light extinction coefficient in Mm^{-1} (top figure) and sulfate fraction in percent of aerosol light extinction (bottom figure), for each of the sites in the IMPROVE network in the United States for the three-year period, March 1988 through February 1991.

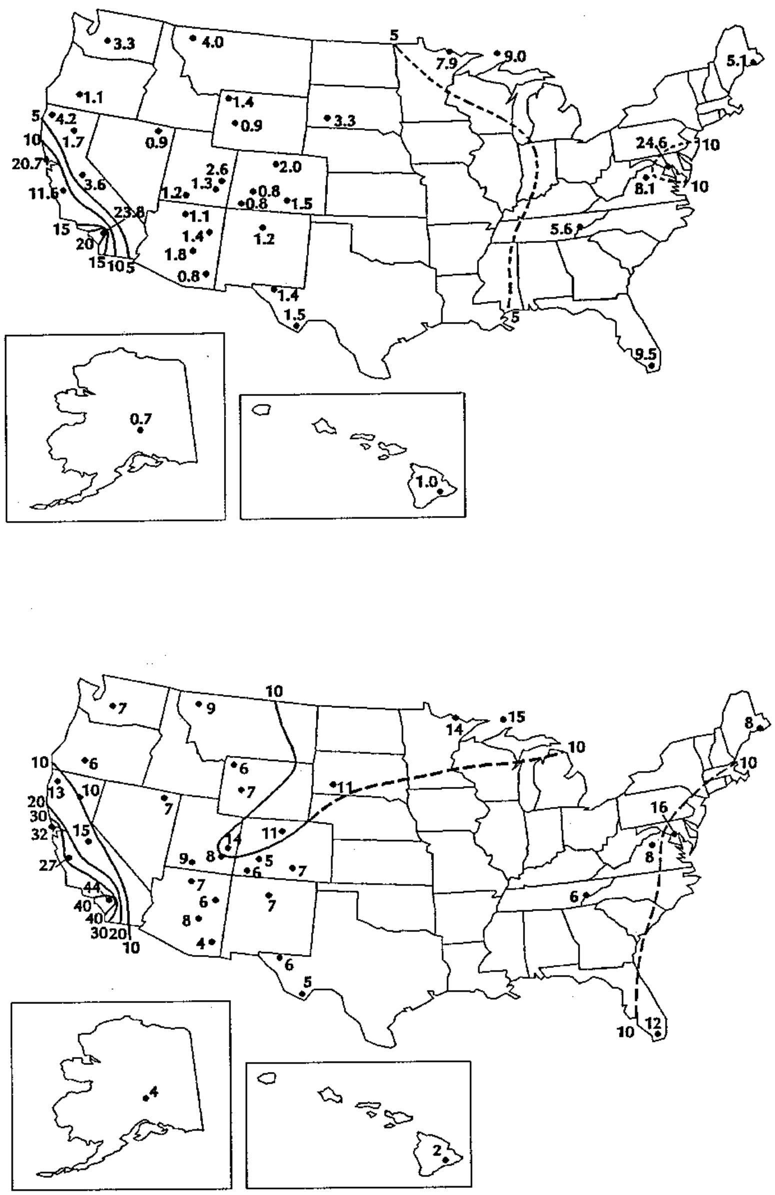


Figure 6.10. Three-year averages of reconstructed nitrate light extinction coefficient in Mm^{-1} (top figure) and nitrate fraction in percent of aerosol light extinction (bottom figure), for each of the sites in the IMPROVE network in the United States for the three-year period, March 1988 through February 1991.

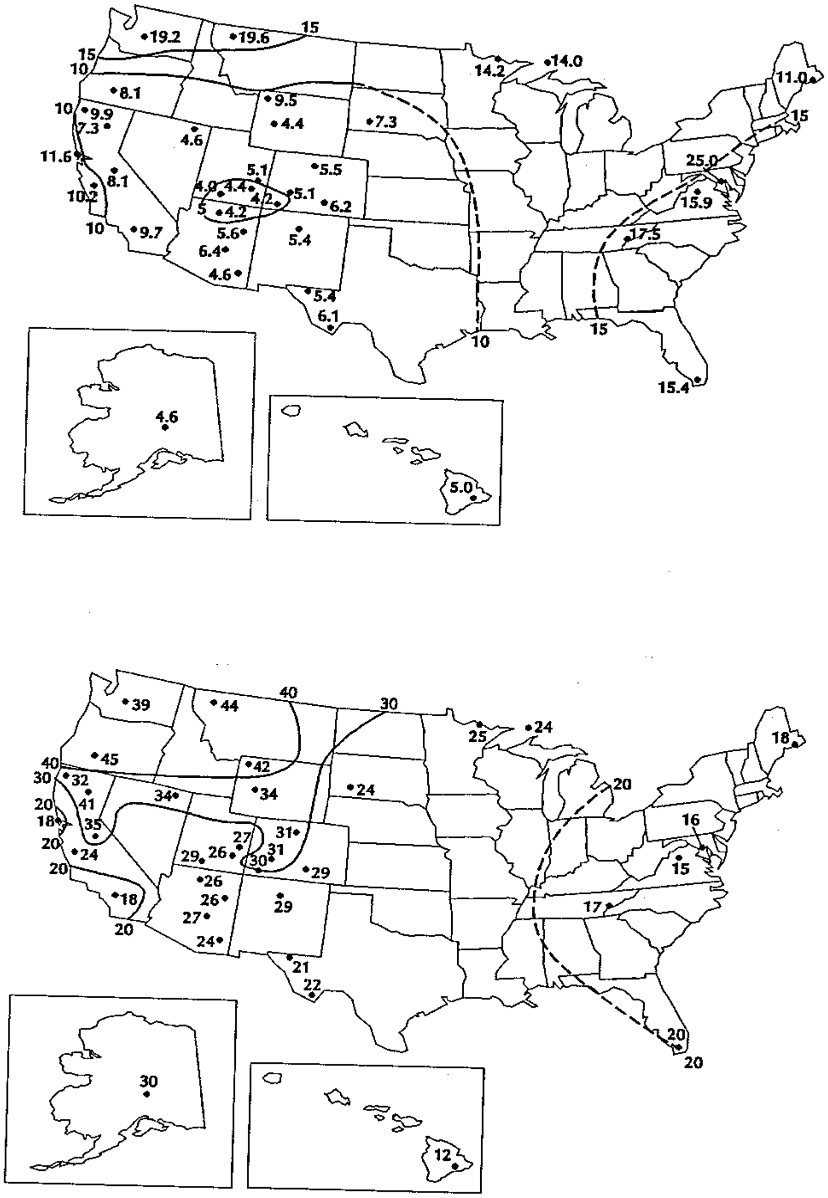


Figure 6.11. Three-year averages of reconstructed organic carbon light extinction coefficient in Mm^{-1} (top figure) and organic carbon fraction in percent of aerosol light extinction (bottom figure), for each of the sites in the IMPROVE network in the United States for the three-year period, March 1988 through February 1991.

Isopleths of dv for the winter, spring, summer, and autumn are shown in Figure 6.14 through Figure 6.17, 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's generally occur in all or part of the Great Basin, Colorado Plateau, and Central Rockies with gradients of increasing dv in any direction. One interesting exception to this occurs in the winter (Figure 6.14), which shows an "island" of impaired visibility in the middle of the Colorado Plateau region at Canyonlands and Arches with dv's of 11.2 and 14.7, respectively. It is also of interest to note the eastern U.S. is almost uniformly above 15 dv of impairment for all four seasons.

The best visibility occurs during the winter (Figure 6.14) with the minimum dv of 6 being reported at Bridger Wilderness followed by 6.3 dv at Jarbidge. The region of 10 or less dv's encompasses a broad expanse that covers the Sierra-Humboldt, Sierra Nevada, Great Basin, and almost all of the Colorado Plateau and the Central Rockies. In the eastern half of the U.S. the sites with more than 20 dv are Washington D.C. at 27.6 dv, the Everglades in Florida at 20.8 dv, and Isle Royale with 20.6 dv.

Summertime visibilities (Figure 6.16), except for the Coastal Range, are generally the worst. Only small portions of the Great Basin, Central Rockies, and Colorado Plateau regions have impaired visibilities slightly below 10 dv. In the East there is a broad region east of the Mississippi with more than 20 dv of impairment in visibility and a swath that covers the Appalachian and Washington D.C. regions with almost 30 dv of impairment.

Visibility impairment in the spring (Figure 6.15) and autumn (Figure 6.17) are quite comparable. The only significant difference is the shifting of the region with impairment of 10 dv or less from the southeast in the spring to the Northwest in the autumn. In the spring, most of the Great Basin and Central Rockies, all of the Colorado Plateau, and a portion of the Sonoran region have less than 10 dv of impaired visibility. During autumn the Sierra-Humboldt, Great Basin, Colorado Plateau, and the western fringe of the Central Rockies have less than 10 dv of impairment.

6.7 Summary

The following are the major patterns in light extinction reconstructed from aerosol measurements and relative humidity during the first three years of IMPROVE:

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 non-urban West.

2. Major Contributors to Light Extinction. Fine aerosols are the principal contributors to light extinction in the United States. Sulfate is the largest single contributor to light extinction in 12 of 19 regions and is tied for first place in two additional regions. In the eastern United States and in Hawaii, sulfate is the overwhelming contributor. Organic carbon is the single largest contributor to light extinction in

four of 19 regions and is tied for first place in two additional regions. Nitrate was the largest single contributor to light extinction only in Southern California.

3. Smaller Contributors. After sulfate and organic carbon, nitrate and windblown dust (coarse particles and fine soil) generally contribute equal amounts. Light absorbing carbon is generally the smallest contributor.

4. Seasonality. 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 relatively elevated sulfate and carbonaceous aerosol concentrations