Appendix C

Methodology for Calculating Light Extinction from Monitored Aerosol Mass Data

Under the IMPROVE visibility monitoring program, particulate matter samples are collected at each monitoring site (see Figure C–1) twice a week (the sampling frequency will change to one sample every three days beginning in the year 2000). Each sample is collected over a 24-hour period on special teflon, nylon, and quartz filters. The filters are weighed and analyzed according to specific protocols to determine the total mass of particulate matter collected, and to determine the portion of the total mass that can be attributed to specific components of PM (e.g., sulfate, nitrate, organic carbon, elemental carbon, and crustal material). Quality assurance procedures are followed for filter handling, chemical analysis, and raw data reporting.

Figure C–1. Locations of IMPROVE Particulate Matter Samplers Operating Continuously from 1994–1998 (Green Shaded Areas Represent Mandatory Federal Class I Areas)

A separate data record is established for each 24-hour sampling period for each site. This data record includes levels of total PM_{10} mass, $PM_{2.5}$ mass, mass for each $PM_{2.5}$ component (each expressed in nanograms per cubic meter, or ng/m^3), and the uncertainty associated with the measurements.[1] Associated light extinction levels are calculated using a standard methodology, hereafter referred to as the IMPROVE methodology. The methodology for calculating light extinction (expressed in inverse megameters, or Mm^{-1}) from speciated PM data has been developed and refined by scientists with the IMPROVE monitoring program.

Total light extinction is expressed as the sum of the following components:

- Light scattering due to particles—caused by both fine and coarse particulate matter. Scattering is the largest contributor to total light extinction in most locations.
- Light absorption due to particles—caused exclusively by carbon-containing particles.
- Light scattering due to natural gases—also known as Rayleigh scattering, or the scattering of light due to the gases (e.g. nitrogen and oxygen molecules) that make up clear sky. Rayleigh scattering is assumed to account for 10 Mm^{-1} at 1.8 kilometers elevation above sea level.
- Light absorption due to gases—caused primarily by nitrogen dioxide (NO_2). Assumed to be negligible in rural Class I areas.

The IMPROVE methodology calculates light extinction attributable to each of the five main components of $PM_{2.5}$ and to coarse PM by multiplying the mass of each component by the light scattering coefficient for that component (or, in the case of elemental carbon, the light absorption coefficient). The scattering coefficients for sulfate, nitrate, organic carbon, fine soil, and coarse PM are 3, 3, 4, 1, and 0.6 m^2/g. The standard light absorption coefficient for elemental carbon is 10 m^2/g. The current IMPROVE methodology for calculating light extinction (in Mm^{-1}) from aerosol mass is described by the following equation:

$$\begin{aligned}\text{Total Light Extinction} = {} & [\text{sulfate mass}] \times [3\ m^2/g] \times f(RH) \\ & + [\text{nitrate mass}] \times [3\ m^2/g] \times f(RH) \\ & + [\text{organic carbon mass}] \times [4\ m^2/g] \\ & + [\text{elemental carbon mass}] \times [10\ m^2/g] \\ & + [\text{fine soil}] \times [1\ m^2/g] \\ & + [\text{coarse mass}] \times [0.6\ m^2/g] \\ & + \text{Rayleigh scattering, or } 10\ Mm^{-1}\end{aligned}$$

where f(RH) is a relative humidity adjustment factor to account for the water uptake by some particles.

Footnote:

[1] During the 1990s, scientists discovered that the IMPROVE Module A filter size was insufficient to capture accurate measurements of high sulfur concentrations. Therefore, the filter sizes were increased and the measurements rose. Since this study examined trends back to 1988, the measurements in this study reflect the sulfate ion measurements from the IMPROVE Module B filter to avoid this change in Module A sample collection.

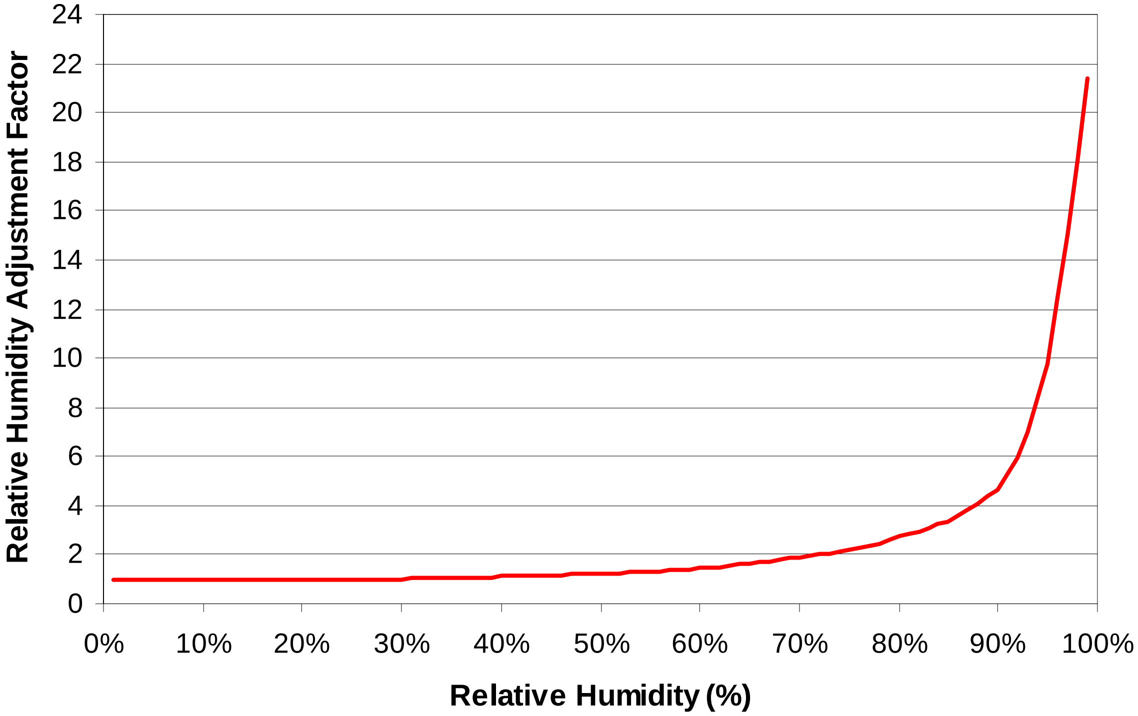

Figure C–2. Relative Humidity Adjustment Factor, f(RH), used to Calculate Light Extinction

Because sulfate and nitrate particles take on water from the atmosphere and become more efficient at scattering light under humid conditions, the IMPROVE methodology for calculating light extinction multiplies sulfate and nitrate mass by a relative humidity adjustment factor, f(RH), which varies with the average relative humidity at the site. Figure C–2, derived from analyses of parallel humidity monitoring at a number of IMPROVE sites, illustrates how the relative humidity adjustment factor increases with higher relative humidity values.

To date, hourly humidity values in excess of 98% have been disregarded in calculating average f(RH) values since it is likely that such readings occur during precipitation events. Table C–1 lists the relative humidities used for calculations at each IMPROVE Monitoring site.

The inverse distance units used to describe light extinction coefficients are difficult to interpret as humanly perceptible changes in visibility. Therefore, the *deciview haze index (dv)* was developed and is calculated directly from the total light extinction coefficient (b_{ext} expressed in Mm^{-1}):

$$dv = 10 \ln (b_{ext} / 10\ Mm^{-1})$$

The deciview scale is nearly zero for a pristine atmosphere (*dv* equals zero for Rayleigh scattering at approximately 1.8 km elevation), and each deciview change corresponds to a small but perceptible scenic change that is observed under either clean or polluted conditions. Like the decibel scale for sound, similar changes in deciviews are perceived as equal. This report includes many trends expressed as deciview changes. Each deciview decrease approximates a perceptible improvement in visibility.

Table C–1. Relative Humidity Adjustment Factors by Season for Each IMPROVE Site

Code	State	Site Name	Elevation (Feet)	Latitude (Degrees)	Longitude (Degrees)	f(RH)			
						Spring	Summer	Autumn	Winter
ACAD	ME	Acadia NP	420	44.3833	68.2667	3.18	3.35	3.83	3.54
BADL	SD	Badlands NM	2,493	43.7500	101.9333	2.63	2.54	2.36	2.63
BAND	NM	Bandelier NM	6,500	35.7833	106.2667	1.68	1.75	1.80	2.15
BIBE	TX	Big Bend NP	3,500	29.3000	103.1833	1.46	1.62	1.78	1.76
BOWA	MN	Boundary Waters CA	1,700	47.9500	91.5167	2.53	3.13	3.91	3.63
BRCA	UT	Bryce Canyon NP	7,997	37.6167	112.1667	3.68	2.16	1.92	2.40
BRID	WY	Bridger WA	8,000	42.9500	109.7500	2.32	1.63	2.16	2.44
BRIG	NJ	Brigantine Div. of EB Forsythe NWR	50	39.4667	74.4500	4.02	4.17	3.20	2.89
CANY	UT	Canyonlands NP	5,950	38.4500	109.8167	1.52	1.24	1.64	2.34
CHAS	FL	Chassahowitzka NWR	10	28.7500	82.5667	3.76	4.27	4.53	3.75
CHIR	AZ	Chiricahua NM	5,400	32.0167	109.3500	1.39	1.81	1.65	2.20
CRLA	OR	Crater Lake NP	6,500	42.8833	122.1333	2.92	2.27	2.11	3.10
DENA	AK	Denali NP	2,100	63.7333	148.9667	2.25	2.65	3.65	3.01
DOSO	WV	Dolly Sods WA	3,800	39.1000	79.4333	3.33	3.63	3.49	4.41
GLAC	MT	Glacier NP	3,200	48.5000	113.9833	3.92	3.41	4.09	4.49
GRBA	NV	Great Basin NP	6,800	39.00003	114.2000	1.75	1.39	1.71	2.02
GRCA	AZ	Grand Canyon NP	7,100	36.0667	112.1500	1.72	1.42	1.68	2.59
GRSA	CO	Great Sand Dunes NM	8,200	37.7333	105.5000	4.26	1.70	2.02	2.11
GRSM	TN	Great Smoky Mtns NP	2,700	35.6333	83.9167	2.68	3.40	3.31	3.64
GUMO	TX	Guadalupe Mtns NP	5,400	31.8500	104.8167	1.55	1.83	1.94	2.04
INGA	AZ	Indian Garden	3,800	36.0667	112.1333	1.69	1.27	1.57	2.38
JARB	NV	Jarbidge WA	6,200	41.8833	115.4167	2.15	1.77	1.82	1.95
LAVO	CA	Lassen Volcanic NP	5,900	40.5333	121.5667	2.45	4.08	1.81	2.52
LOPE	UT	Lone Peak WA	6,200	40.4500	111.7000	2.00	1.50	2.07	2.85
LYBR	VT	Lye Brook WA	3,250	43.1667	73.0000	2.58	3.96	4.28	3.09

Table C–1. Relative Humidity Adjustment Factors by Season for Each IMPROVE Site *(continued)*

Code	State	Site Name	Elevation (Feet)	Latitude (Degrees)	Longitude (Degrees)	f(RH)			
						Spring	Summer	Autumn	Winter
MACA	KY	Mammoth Cave NP	750	37.2167	86.0667	3.34	6.82	4.81	3.42
MEVE	CO	Mesa Verde NP	7,210	37.2000	108.4833	1.57	1.61	1.71	2.52
MOOS	ME	Moosehorn NWR	130	45.1167	67.2833	3.18	3.35	3.83	3.54
MORA	WA	Mount Rainier NP	1,430	46.7500	122.1167	6.01	4.86	7.36	7.40
MOZI	CO	Mount Zirkel WA	10,557	40.5500	106.7000	2.37	1.32	2.02	2.42
OKEF	GA	Okefenokee NWR	50	30.7333	82.1167	3.92	4.97	5.34	4.28
PEFO	AZ	Petrified Forest NP	5,500	35.0731	109.7739	1.47	1.51	1.72	2.37
PINN	CA	Pinnacles NM	1,040	36.4833	121.1667	2.81	2.09	2.11	2.83
PORE	CA	Point Reyes NS	125	38.1167	122.9000	4.11	5.50	3.65	3.49
REDW	CA	Redwood NP	760	41.5500	124,0833	8.27	5.84	8.50	6.41
ROMA	SC	Cape Romain NWR	8	32.9400	79.6600	3.92	4.97	5.34	4.28
ROMO	CO	Rocky Mountain NP	7,900	40.3833	105.5667	2.15	1.96	1.84	1.70
SAGO	CA	San Gorgonio WA	5,618	34.2000	116.9167	2.58	1.56	1.72	2.96
SEQU	CA	Sequoia NP	1,800	36.4989	118.8239	2.51	1.37	1.80	3.17
SHEN	VA	Shenandoah NP	3,600	38.5500	78.4000	3.10	4.45	3.80	3.77
SHRO	NC	Shining Rock WA	5,290	35.3933	82.7764	3.31	5.06	3.26	3.56
SIPS	AL	Sipsey WA	600	34.3333	87.3333	3.16	5.43	4.70	3.58
SNPA	WA	Snoqualmie Pass	3,600	47.4167	121.4167	4.45	3.33	5.37	6.30
THSI	OR	Three Sisters WA	2,850	44.2833	122.0500	4.83	3.03	4.80	6.98
TONT	AZ	Tonto NM	2,600	33.6500	111.1000	1.32	1.32	1.27	1.76
UPBU	AR	Upper Buffalo WA	2,300	35.8333	93.2167	3.01	3.46	2.97	3.30
WASH	DC	DC National Mall	30	38.8833	77.5000	2.69	3.01	3.14	2.59
WEMI	CO	Weminuche WA	9,050	37.6500	107.8000	4.85	1.61	2.15	2.34
YELL	WY	Yellowstone NP	7,744	44.5500	110.4000	2.50	2.16	2.01	1.97
YOSE	CA	Yosemite NP	5,300	37.7000	119.7000	2.51	1.37	1.80	3.16

CA	Canoe Area
NM	National Monument
NP	National Park
NWR	National Wildlife Refuge
WA	Wilderness Area