APPENDIX E

REGIONAL HAZE CALCULATION CONSTANTS

1.0 INTRODUCTION

The analysis of the regional haze improvement goals presented in Chapter 8, involves estimating visibility changes using an equation for light extinction. This equation requires data that is not readily estimated using the source-receptor matrix discussed in Chapters 4 and 6. This data is currently available for several Class I areas that contain monitors in the IMPROVE network. Data collected from these monitors for the years 1992 - 1995 is used in this analysis to fill-in the missing values. In this analysis, these values are assumed constant. Since in reality, some of these values are expected to change due to changes in emissions, holding these values constant understates the impact that certain emission reducing control measures are likely to have on visibility improvement.

2.0 CONCENTRATION AND RELATIVE HUMIDITY CONSTANTS

This section presents the concentration and relative humidity constants used to calculate atmospheric light extinction. The total atmospheric light extinction coefficient (b_{ext}) can be calculated as the summation of the individual scattering and absorption extinctions as shown in Equation 1.

$$b_{ext} = b_{sp} + b_{ab} + b_{sg} + b_{ag} \qquad \textit{Equation (1)}$$

where:

b_{sp} = light scattering due to particles;
b_{ab} = light absorption due to particles;
b_{sg} = light scattering due to gases;
b_{ag} = light absorption due to gases.

These four extinctions can be individually estimated based on a knowledge of the atmospheric concentrations and physical properties of the light scattering or absorption species that contribute to light extinction. Table E.1 lists the empirical coefficients C1 (*f*(RH)), C2 (OMC), C3 (b_{abs}), and C4 (SOIL) developed that are used in the equations described below to calculate visibility in counties containing Class I areas.

1. Light Scattering Due to Particles (b_{sp})

Light is scattered by particles suspended in the atmosphere, and the efficiency of this scattering per unit mass concentration is largest for particles with sizes comparable to the wavelength of light (~500 nm). These particles may result from natural sources, such as animal and plant organic material, aeolian dust, volcanic eruptions, and sea salt. When visibility is poor, however, most particles are found to be of manmade origin, from sources such as power plants, vehicle exhaust, biomass burning, suspended dust, and industrial activities. The most common chemical components of these particles include carbon, sulfate, nitrate, ammonium, and crustal materials (i.e., oxides of silicon, aluminum, iron, titanium, calcium, and other elements). The degree to which particles composed of these chemicals scatter light depends on their size, shape, and index of refraction.

In addition, atmospheric water is another important component of suspended PM. The liquid water content of ammonium nitrate, ammonium sulfate, and other soluble species increases with relative humidity, and is especially important when relative humidity exceeds 70 percent. Particles containing these compounds grow into the droplet mode as they take on liquid water, so the same concentration of sulfate or nitrate makes a much larger contribution to light extinction when humidities are high (>70 percent) than when they are low (<30 percent).

Table E.1 Regional Haze Constants for the Effects of Relative Humidity on Sulfate and Nitrate Scattering (*f*(RH)), Organic Aerosols (OMC), Elemental Carbon Absorption (b_{abs}), and Fine Soil (SOIL)

County	Class I Area Name	*f*(RH)	OMC	b_{abs}	SOIL
Lawrence Co AL	Sipsey W	4.453	4.041	19.445	0.607
Apache Co AZ	Mount Baldy W	2.121	1.490	7.500	0.508
Apache Co AZ	Petrified Forest NP	2.121	1.490	7.500	0.508
Cochise Co AZ	Chiricahua W	1.915	1.173	5.024	0.566
Coconino Co AZ	Sycamore Canyon W	2.015	1.132	4.441	0.446
Coconino Co AZ	Grand Canyon NP	2.015	1.132	4.441	0.446
Gila Co AZ	Sierra Ancha W	2.017	1.265	5.655	0.506
Gila Co AZ	Mazatzal W	2.017	1.265	5.655	0.506
Graham Co AZ	Galiuro W	1.915	1.173	5.024	0.566
Maricopa Co AZ	Superstition W	2.017	1.265	5.655	0.506
Pima Co AZ	Saguaro W	1.915	1.173	5.024	0.566
Yavapai Co AZ	Pine Mountain W	2.017	1.265	5.655	0.506
Madison Co AR	Upper Buffalo W	4.282	2.925	11.207	0.573
Polk Co AR	Caney Creek W	4.282	2.925	11.207	0.573
Calaveras Co CA	Mokelumme W	3.201	1.629	5.323	0.391
Del Norte Co CA	Redwood NP	7.116	1.497	3.845	0.126
El Dorado Co CA	Desolation W	3.201	1.629	5.323	0.391
Fresno Co CA	John Muir W	2.435	2.061	6.897	0.518
Fresno Co CA	Kaiser W	2.435	2.061	6.897	0.518
Fresno Co CA	Kings Canyon NP	2.435	2.061	6.897	0.518
Lassen Co CA	Caribou W	2.714	1.520	4.334	0.423
Los Angeles Co CA	San Gabriel W	2.140	2.684	10.146	0.878
Marin Co CA	Point Reyes W	4.453	1.306	4.736	0.233
Mariposa Co CA	Yosemite NP	2.435	2.061	6.897	0.518
Modoc Co CA	South Warner W	2.714	1.520	4.334	0.423
Mono Co CA	Minarets W	2.435	2.061	6.897	0.518
Monterey Co CA	Ventana W	2.757	2.026	8.663	0.423
Riverside Co CA	San Jacinto W	2.140	2.684	10.146	0.878
Riverside Co CA	Joshua Tree W	2.140	2.684	10.146	0.878
San Benito Co CA	Pinnacles W	2.757	2.026	8.663	0.423
San Bernardino Co CA	Cucamonga W	2.140	2.684	10.146	0.878
San Bernardino Co CA	San Gorgonio W	2.140	2.684	10.146	0.878
San Diego Co CA	Agua Tibia W	2.140	2.684	10.146	0.878
Santa Barbara Co CA	San Rafael W	2.287	2.373	8.521	0.698
Shasta Co CA	Thousand Lakes W	2.714	1.520	4.334	0.423
Shasta Co CA	Lassen Volcanic NP	2.714	1.520	4.334	0.423
Siskiyou Co CA	Marble Mountain W	7.116	1.497	3.845	0.126
Siskiyou Co CA	Lava Beds W	2.714	1.520	4.334	0.423

County	Class I Area Name	*f*(RH)	OMC	b_{abs}	SOIL
Trinity Co CA	Yolla-Bolly-Middle-Eel	2.714	1.520	4.334	0.423
Tulare Co CA	Sequoia NP	2.435	2.061	6.897	0.518
Tulare Co CA	Dome Land W	2.287	2.373	8.521	0.698
Tuolumne Co CA	Emigrant W	2.435	2.061	6.897	0.518
Tuolumne Co CA	Hoover W	2.435	2.061	6.897	0.518
Garfield Co CO	Flat Tops W	2.078	1.305	4.454	0.559
Gunnison Co CO	West Elk W	2.350	1.262	4.108	0.533
Larimer Co CO	Rawah W	2.078	1.305	4.454	0.559
Larimer Co CO	Rocky Mountain NP	2.078	1.305	4.454	0.559
Mineral Co CO	La Garita W	2.350	1.262	4.108	0.533
Montezuma Co CO	Mesa Verde NP	2.158	1.178	3.993	0.453
Montrose Co CO	Black Canyon of the Gun	2.350	1.262	4.108	0.533
Pitkin Co CO	Maroon Bells-Snowmass W	2.078	1.305	4.454	0.559
Routt Co CO	Mount Zirkel W	2.078	1.305	4.454	0.559
Alamosa Co CO	Great Sand Dunes W	2.350	1.262	4.108	0.533
San Juan Co CO	Weminuche W	2.485	1.141	4.806	0.446
Summit Co CO	Eagles Nest W	2.078	1.305	4.454	0.559
Citrus Co FL	Chassahowitzka W	4.453	2.965	15.481	0.642
Monroe Co FL	Everglades NP	4.453	2.965	15.481	0.642
Wakulla Co FL	St Marks W	4.047	2.989	13.189	0.518
Charlton Co GA	Okefenokee W	4.047	2.989	13.189	0.518
McIntosh Co GA	Wolf Island W	4.047	2.989	13.189	0.518
Butte Co ID	Craters of the Moon W	2.267	1.292	3.719	0.613
Elmore Co ID	Sawtooth W	2.267	1.292	3.719	0.613
Idaho Co ID	Selway-Bitterroot W	2.267	1.292	3.719	0.613
Edmonson Co KY	Mammoth Cave NP	3.979	3.287	17.624	0.374
Hancock Co ME	Acadia NP	4.073	1.867	8.199	0.191
Washington Co ME	Roosevelt Campobello IP	4.073	1.867	8.199	0.191
Washington Co ME	Moosehorn	4.073	1.867	8.199	0.191
Keweenaw Co MI	Isle Royal NP	3.661	1.670	5.344	0.262
Schoolcraft Co MI	Seney W	3.661	1.670	5.344	0.262
St. Louis Co MN	Boundary Waters Canoe A	3.661	1.670	5.344	0.262
St. Louis Co MN	Voyageurs NP	3.661	1.670	5.344	0.262
Stone Co MS	Breton W	4.453	4.041	19.445	0.607
Taney Co MO	Hercules-Glades W	4.282	2.925	11.207	0.573
Wayne Co MO	Mingo W	4.282	2.925	11.207	0.573
Beaverhead Co MT	Anaconda-Pintlar W	3.677	2.113	6.587	0.536
Beaverhead Co MT	Red Rock Lakes W	2.234	1.273	3.660	0.520
Flathead Co MT	Glacier NP	5.107	2.776	8.951	0.441
Lewis and Clark Co MT	Bob Marshall W	5.107	2.776	8.951	0.441
Lewis and Clark Co MT	Scapegoat W	5.107	2.776	8.951	0.441
Lewis and Clark Co MT	Gates of the Mtn W	3.677	2.113	6.587	0.536

County	Class I Area Name	f(RH)	OMC	b_{abs}	SOIL
Missoula Co MT	Mission Mountain W	5.107	2.776	8.951	0.441
Phillips Co MT	U.L. Bend W	3.677	2.113	6.587	0.536
Sanders Co MT	Cabinet Mountains W	5.107	2.776	8.951	0.441
Sheridan Co MT	Medicine Lake W	3.016	1.427	5.795	0.419
Elko Co NV	Jarbidge W	2.288	1.134	3.215	0.593
Coos Co NH	Presidential Range-Dry	4.337	1.511	6.865	0.216
Grafton Co NH	Great Gulf W	4.337	1.511	6.865	0.216
Atlantic Co NJ	Brigantine W	2.488	2.727	15.348	0.427
Chaves Co NM	Salt Creek W	2.192	1.420	6.168	0.779
Eddy Co NM	Carlsbad Caverns NP	2.192	1.420	6.168	0.779
Grant Co NM	Gila W	2.076	1.361	6.231	0.618
Lincoln Co NM	White Mountain W	2.076	1.361	6.231	0.618
Mora Co NM	Pecos W	2.053	1.419	5.172	0.478
Rio Arriba Co NM	San Pedro Parks W	2.053	1.419	5.172	0.478
Sandoval Co NM	Bandelier W	2.053	1.419	5.172	0.478
Socorro Co NM	Bosque del Apache W	2.076	1.361	6.231	0.618
Taos Co NM	Wheeler Peak W	2.350	1.262	4.108	0.533
Avery Co NC	Linville Gorge W	3.106	2.906	15.216	0.462
Graham Co NC	Joyce Kilmer-Slickrock	3.106	2.906	15.216	0.462
Haywood Co NC	Shining Rock W	3.106	2.906	15.216	0.462
Hyde Co NC	Swanguarter W	4.207	2.508	14.723	0.408
Burke Co ND	Lostwood W	3.016	1.427	5.795	0.419
McKenzie Co ND	Theodore Roosevelt NMP	3.016	1.427	5.795	0.419
Comanche Co OK	Wichita Mountains W	4.282	2.925	11.207	0.573
Curry Co OR	Kalmiopsis W	7.116	1.497	3.845	0.126
Grant Co OR	Strawberry Mountain W	5.527	2.178	7.509	0.351
Hood River Co OR	Mount Hood W	7.435	2.490	8.636	0.197
Jefferson Co OR	Mount Washington W	4.039	1.268	4.939	0.415
Klamath Co OR	Crater Lake NP	4.039	1.268	4.939	0.415
Klamath Co OR	Mountain Lakes W	4.039	1.268	4.939	0.415
Lake Co OR	Gearhart Mountain W	4.039	1.268	4.939	0.415
Lane Co OR	Three Sisters W	4.039	1.268	4.939	0.415
Lane Co OR	Diamond Peak W	4.039	1.268	4.939	0.415
Marion Co OR	Mount Jefferson W	4.039	1.268	4.939	0.415
Union Co OR	Eagle Cap W	5.527	2.178	7.509	0.351
Wallowa Co OR	Hells Canyon W	5.527	2.178	7.509	0.351
Custer Co SD	Wind Cave NP	3.016	1.427	5.795	0.419
Jackson Co SD	Badlands W	3.016	1.427	5.795	0.419
Polk Co TN	Cohotta W	3.106	2.906	15.216	0.462
Blount Co TN	Great Smokey Mountains	3.106	2.906	15.216	0.462
Brewster Co TX	Big Bend NP	1.895	1.597	7.178	0.771
Culberson Co TX	Guadalupe Mountains NP	2.192	1.420	6.168	0.779

County	Class I Area Name	*f*(RH)	OMC	b_{abs}	SOIL
Garfield Co UT	Bryce Canyon NP	2.558	1.096	4.108	0.472
San Juan Co UT	Capitol Reef NP	1.880	1.194	4.571	0.584
San Juan Co UT	Canyonlands NP	1.880	1.194	4.571	0.584
Grand Co UT	Arches NP	1.880	1.194	4.571	0.584
Washington Co UT	Zion NP	2.558	1.096	4.108	0.472
Bennington Co VT	Lye Brook W	4.337	1.511	6.865	0.216
Botetourt Co VA	James River Face W	4.207	2.508	14.723	0.408
Madison Co VA	Shenandoah NP	4.207	2.508	14.723	0.408
Jefferson Co WA	Olympic NP	7.435	2.490	8.636	0.197
King Co WA	Alpine Lakes W	7.435	2.490	8.636	0.197
Okanogan Co WA	Pasayten W	7.435	2.490	8.636	0.197
Okanogan Co WA	Glacier Peak W	7.435	2.490	8.636	0.197
Lewis Co WA	Mount Rainer NP	7.435	2.490	8.636	0.197
Whatcom Co WA	North Cascades NP	7.435	2.490	8.636	0.197
Yakima Co WA	Goat Rocks W	7.435	2.490	8.636	0.197
Yakima Co WA	Mount Adams W	7.435	2.490	8.636	0.197
Grant Co WV	Dolly Sods W	4.587	3.210	13.057	0.336
Tucker Co WV	Otter Creek W	4.587	3.210	13.057	0.336
Fremont Co WY	Fitrzatrick W	2.234	1.273	3.660	0.520
Teton Co WY	Yellowstone NP	2.234	1.273	3.660	0.520
Park Co WY	North Absaroka W	2.234	1.273	3.660	0.520
Park Co WY	Washakie W	2.234	1.273	3.660	0.520
Park Co WY	Teton W	2.234	1.273	3.660	0.520
Sublette Co WY	Bridger W	2.234	1.273	3.660	0.520
Teton Co WY	Grand Teton NP	2.234	1.273	3.660	0.520

The contributions of light scattering due to particles can be estimated by summing the individual light scattering effects of fine particle ammonium sulfate, fine particle ammonium nitrate, fine particle organic carbon, fine particle soil, and coarse particle mass (coarse particle mass is defined as mass difference between PM_{10} and $PM_{2.5}$). The individual scattering effect of each component is calculated by combining the pollutant concentration (in $\mu g/m^3$), coefficient, and extinction efficiency (m^2/g) as:

*fine particle ammonium sulftate = C1 * [Conc. of $(NH_4)_2SO_4$) $\mu g/m^3$ * 3.0 m^2/g* *Equation (2)*

*fine particle ammonium nitrate = C1 * [Conc. of (NH_4NO_3) $\mu g/m^3$ * 3.0 m^2/g* *Equation (3)*

*fine particle organic carbon = C2 $\mu g/m^3$ * 3.0 m^2/g* *Equation (4)*

fine particle soil = C4 Mm^{-1} *Equation (5)*

*coarse particle mass = [Conc. of Coarse particle mass] $\mu g/m^3$ * 0.6 m* *Equation (6)*

Where, C1describes the annual relativity humidity effect of scattering on fine particle ammonium sulfate and ammonium nitrate (*f*(RH)), and C2 and C4 describe the organic carbon and fine particle concentrations observed at each area, respectively (OMC and SOIL). The total light scattering due to particles (at each Class I area) is simply the summation of the individual scattering effects determined by Equations 2 through 6.

2. Light Absorption Due to Particles (b_{ab})

Elemental carbon (EC or black carbon) makes the most significant contribution to particle light absorption. High concentrations are seldom found in emissions from efficient combustion sources, though EC is abundant in motor vehicle exhaust, fires, and residential heating emissions. Additional light absorption has been shown in other studies to be caused by minerals in coarse particles, but its contribution is usually small. Horvath (1993) shows, from theoretical considerations and measurements, that each μg/m^3 of "black carbon" typically contributes 8 to 12 m^2/g to extinction. The site specific absorption reported values used for this study were derived from IMPROVE filter measurements made by the laser integrated plate method. This site specific absorption is shown as C_3 in Table 4.2 in units of Mm^{-1}.

3. Light Scattering by Gases (b_{ag})

The presence of atmospheric gases such as oxygen and nitrogen limits horizontal visual range to ~400 km and obscures many of the attributes of a target at less than half this distance. This "Rayleigh scattering" in honor of the scientist who elucidated this phenomena, is the major component of light extinction in areas where pollution levels are low, has a scattering coefficient of ~10 Mm^{-1}, and it can be accurately estimated from temperature and pressure measurements (Edlen, 1953; Penndorf, 1957). Values range from 9 Mm^{-1} at high altitudes to 12 Mm^{-1} at sea level, but is assumed in this analysis to be constant. A value of 10 Mm^{-1} is used for all sites as an approximation.

4. Light Absorption Due to Gases (b_{sg})

Nitrogen dioxide is the only gas likely to be present in Class I Areas that would cause significant absorption of visible light. Each μg/m^3 of nitrogen dioxide contributes ~0.17 Mm^{-1} of extinction at ~550 nm wavelengths (Dixon, 1940), so NO_2 concentrations in excess of 60 μg/m^3 (30 ppbv) are needed to exceed Rayleigh scattering. This contribution is larger for shorter wavelengths (e.g., blue light) and smaller for longer wavelengths (e.g., red light). For this reason, plumes rich in NO_2 often appear reddish-brown because much of the yellow, blue, and purple light is absorbed. Though NO_2 concentrations are much lower than this in most pristine areas, concentrations of several ppm can be found in coherent plumes near the source concentrations of NO_2 are not available for use in this study and therefore its concentration (and light absorption) is assumed to be negligible.

3.0 AVERAGE ANNUAL 90TH-TO-50TH PERCENTILE DECIVIEW VALUES

The outputs from the source-receptor matrix used to estimate air quality contributions of PM precursor emissions are expressed in terms of annual average values. These outputs are one of the key components of the RH optimization model that is used in this analysis to select control measures. The RH improvement targets analyzed in this analysis are expressed in terms of improvements in the 90th percentile values, or in other words, improvements in the average deciview value in the 20 percent worst days. In order to assess improvements in the average f the 20 percent worst days, a relationship between the 90th percentile deciview value and the mean deciview value must be established. This section contains the data used to establish this relationship.

Table E.2 contains the average annual ratio of the 90th percentile and 50th percentile deciview values for the set of rural IMPROVE Class I area sites from 1993 to 1995. The average ratio for the years 1993 to 1995 ranges from 1.39 to 1.46, with a three year average of 1.42. Using this ratio, a 1.0 deciview improvement in the 90th percentile value is equivalent to a 0.7 deciview improvement in the 50th percentile value. Likewise, a 0.67 deciview improvement in the 90th percentile value is equivalent to a 0.5 deciview improvement in the 50th percentile value.

Table E.2 1993-1995 Annual 90th/50th Percentile Deciview Ratio for Rural IMPROVE Sites Located in Class I Area Counties

Class I Code	Class I Area Name	State	Annual 90th/50th Percentile Ratio		
			1993	1994	1995
ACAD	Acadia	ME	1.51	1.51	1.50
BADL	Badlands	SD	1.45	1.45	1.36
BAND	Bandelier	NM	1.28	1.38	1.47
BIBE	Big Bend	TX	1.30	1.33	1.37
BRCA	Bryce Canyon	UT	1.34	1.25	1.48
BRID	Bridger Wilderness	WY	1.42	1.47	1.51
CANY	Canyonlands	UT	1.27	1.25	1.39
CHIR	Chiricahua	AZ	1.32	1.39	1.39
CRLA	Crater Lake	OR	1.81	1.47	1.75
DENA	Denali	AK	1.89	1.74	1.83
GLAC	Glacier	MT	1.36	1.31	1.41
GRCA	Grand Canyon	AZ	1.37	1.37	1.39
GRSA	Great Sand Dunes	CO	1.36	1.66	1.43
GRSM	Great Smokies	TN	1.21	1.44	1.33
GUMO	Guadalupe Mtns	TX	1.30	1.29	1.28
LAVO	Lassen Volcanic	CA	1.57	1.57	1.59
MEVE	Mesa Verde	CO	1.46	1.29	1.49
MORA	Mt Rainier	WA	1.27	1.43	1.46
PEFO	Petrified Forest	AZ	1.29	1.19	1.46
PINN	Pinnacles	CA	1.20	1.31	1.29
PORE	Pt Reyes	CA	1.66	1.40	1.48
REDW	Redwood	CA	1.44	1.28	1.40
ROMO	Rocky Mtn	CO	1.46	1.34	1.67
SAGO	San Gorgonio	CA	1.25	1.34	1.33
SHEN	Shenandoah	VA	1.23	1.33	1.37
TONT	Tonto	AZ	1.29	1.19	1.29
WEMI	Weminuche	CO	1.32	1.24	1.53
YELL	Yellowstone	WY	1.38	1.68	1.66
YOSE	Yosemite	CA	1.38	1.58	1.50
Annual Average 90th/50th Percentile Ratio			1.39	1.40	1.46
Average of 1993-1995					1.42

4.0 REFERENCES

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