United States
Environmental Protection
Agency

Office of Air Quality
Planning and Standards
Research Triangle Park, NC 27711

EPA-452/R-93-014
October 1993

Air

Effects of the 1990 Clean Air Act Amendments on Visibility in Class I Areas: An EPA Report to Congress

ACKNOWLEDGEMENTS

This report is the product of the U.S. Environmental Protection Agency's (EPA) Office of Air Quality Planning and Standards (OAQPS). Bruce Polkowsky was project coordinator. Marc Pitchford of the EPA Office of Research and Development (ORD) drafted Chapter 2. The analysis of visibility changes for the eastern U.S. was performed by Robin Dennis of the EPA ORD. The preliminary national analysis and the southwestern U.S. analysis were performed by Systems Application International, Inc., under contract with the OAQPS. The report incorporates comments from other staff at the OAQPS, the ORD, the EPA Office of General Counsel, and the EPA Regional Offices.

The work plan for the analyses which support the conclusions of the report was reviewed by representatives from the Department of Energy, the National Park Service, the U.S. Fish and Wildlife Service, the U.S. Forest Service, and by environmental and industrial groups including the Environmental Defense Fund and the Utility Air Regulatory Group in December of 1991. The preliminary results of the western modeling analysis were presented at a public meeting of the Grand Canyon Visibility Transport Commission in January 1993. An informal public review of a draft of the entire report took place in August 1993. Comments on this draft were received from the Utility Air Regulatory Group, the Tennessee Valley Authority, Arizona Public Service Company, and the U.S. Forest Service.

Executive Summary

In this report the EPA has assessed changes in regional visibility expected from implementation of the many provisions of the Clean Air Act Amendments of 1990. This report provides an estimate of future regional visibility conditions for the contiguous 48 United States.

This report used a layered approach to assessing visibility changes. A preliminary assessment was made choosing key locations and a simple emissions-driven air quality assessment to ascertain areas likely to see changes in the distribution of man-made visibility-impairment related pollutants. This preliminary analysis pointed towards a more focused approach for the Eastern U.S., concentrating mostly on changes in sulfur dioxide emissions. For the Southwestern U.S., the mixture of pollutants is more varied and less dominated by sulfur particles. Thus the analysis incorporated changes in emissions of sulfur, nitrogen, organic and primary particulate matter.

Figure ES-1 is a map showing the locations of the Federal mandatory class I areas. Figure ES-2 shows the regions used in preliminary analysis. Figure ES-3 highlights which of these regions were expected to see perceptible changes in visibility conditions. Figure ES-4 shows the general domains of the more advanced regional air quality modeling used in this report.

Figure ES-5 shows the current annual average visibility conditions expressed in standard visual range (kilometers). For the class I areas of the rural southwestern U.S., the annual average visibility conditions generally result from 20 to 40 percent natural causes (gases of the atmosphere, estimated natural fine particles, and coarse particles) and 60 to 80 percent man-made concentrations of aerosols and gases. For the rural eastern U.S., the annual average visibility conditions generally result from 10 to 30 percent natural and 70 to 90 percent man-made concentrations. These relative levels do not apply for class I areas near (within 100-200 km) large urban areas, nor for class I areas directly on the sea coasts. Estimates of emissions changes resulting from implementation of the 1990 Amendments were used to model changes in the man-made portion of the visibility impairment aerosol concentrations for two regions of the country. Seasonal changes were estimated since atmospheric processes which form visibility impairing particles and resulting levels of extinction of those particles (due to humidity) vary by season.

Figure ES-6 shows the estimated change (1988-2005 in the southwest, 1985-2010 in the east) in annual average standard visual range along with a perception index (deciview) for all

Figure ES-1. Map of Mandatory Federal Class I Areas

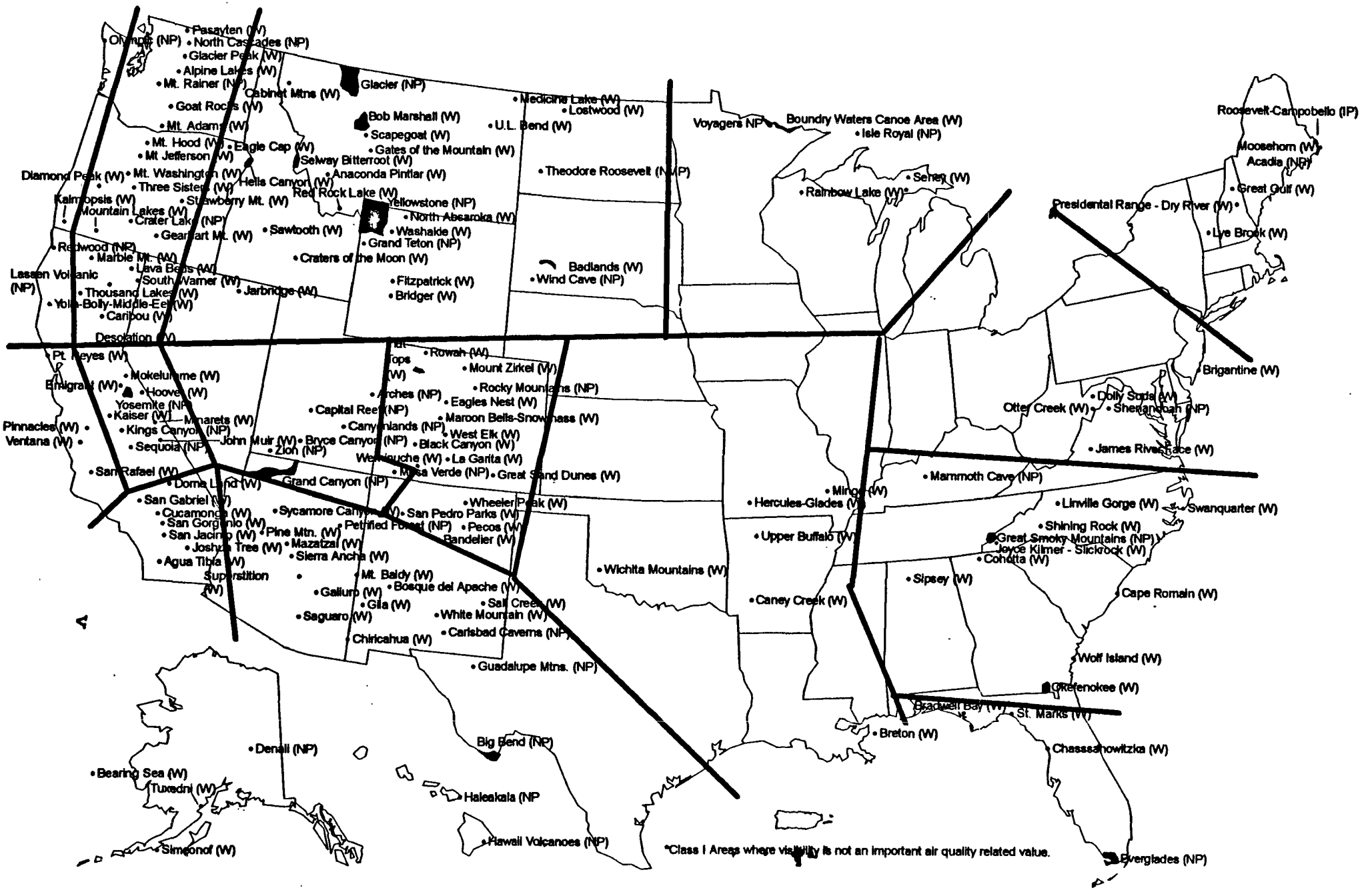

Figure ES-2 Regions Used in Preliminary Analysis

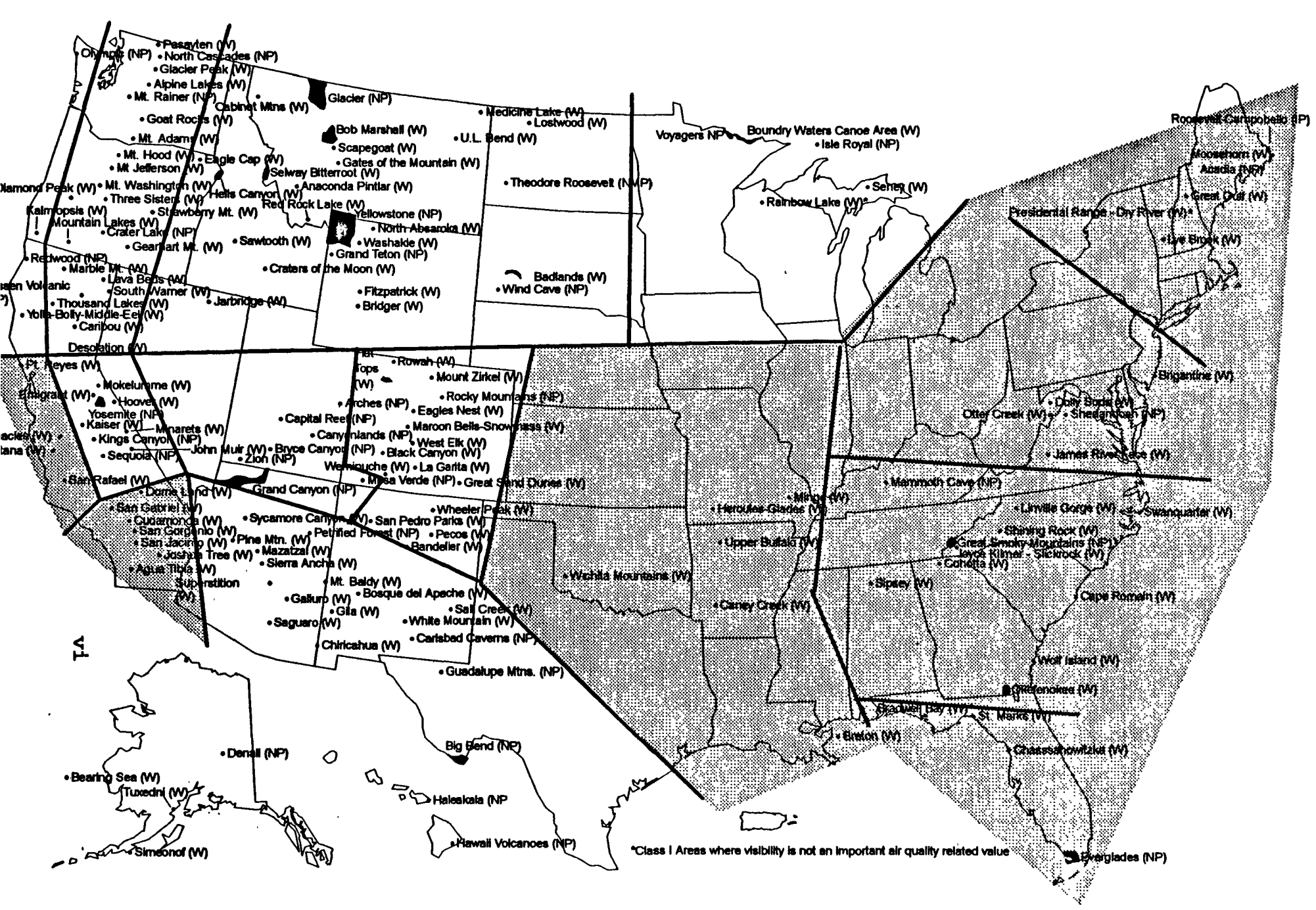

Figure ES-3. Areas Indicating Changes in Regional Visibility Impairment in the Preliminary Analysis

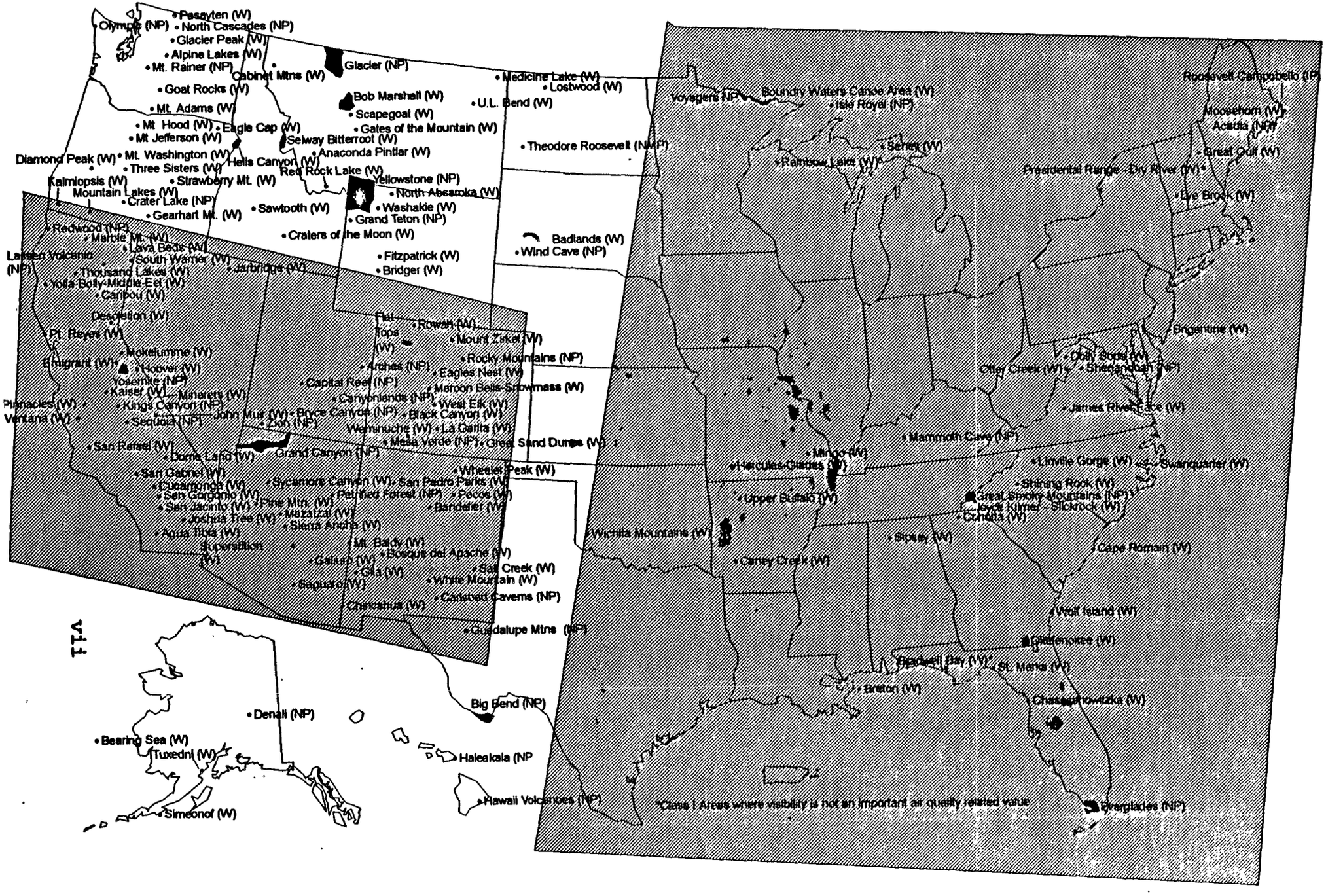

Figure ES-4. Geographic Domains for Air Quality Modeling

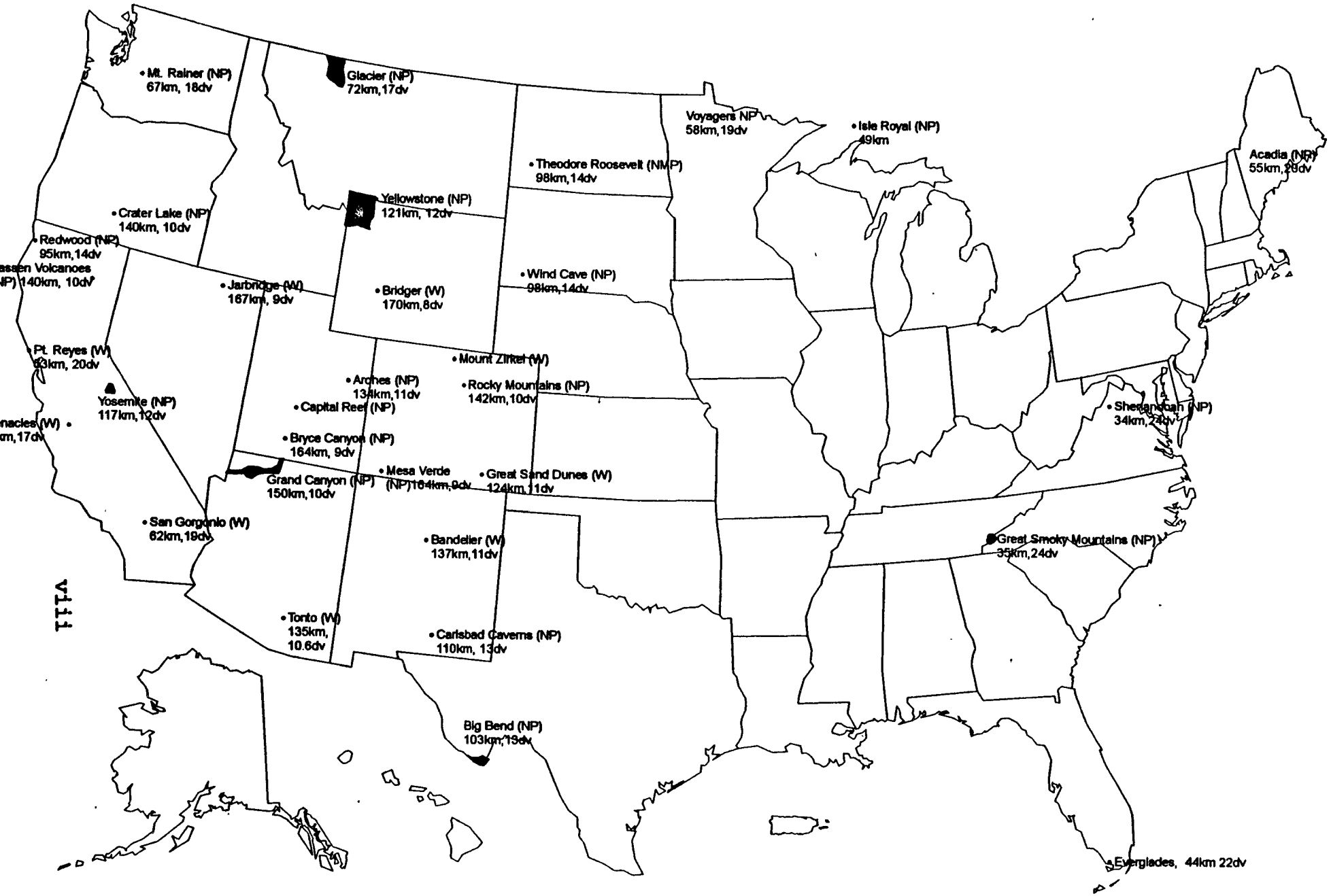

Figure ES-5. Average Visibility Conditions from Monitored Aerosol Data

- Average Standard Visual Range in kilometers. Haziness Index in Deciview
- Source.. IMPROVE report, "Spatial and Temporal Patterns and Chemical Composition of Haze in the United States, February, 1993

Figure ES-6. Class I Areas Expecting a Perceptible Improvement in Annual Average Visibility

Annual Average Visual Range. A 1 dv change is considered perceptible
Nearby Class I Areas should have similar changes in regional visibility as those indicated.

selected class I areas in the modeling domains that are estimated to be perceptible. Nearby class I areas should see similar levels of change. An estimate of 1 deciview change is considered to be just perceptible. All areas outside of the southwestern and eastern modeling areas were estimated, based on the preliminary analysis, to have imperceptible changes in regional visibility due to the Clean Air Act Amendment programs. The class I areas inside of the southwestern and eastern modeling areas not indicated in Figure ES-6 are estimated to have imperceptible changes in annual average or seasonal regional visibility conditions. Figures ES-7 and ES-8 show the estimated visibility change in winter and summer seasons, respectively.

In summary, class I areas from Maine to Georgia are estimated to see improvements in regional visibility conditions. It is very important to note that, under the expected implementation of the Clean Air Act Amendments, no class I areas are estimated to have perceptible decreases in regional visibility. Winter and summer seasons show improvements ranging from just perceptible to six times perceptible. The major improvements expected for class I areas are for those along the central and southern portions of the Appalachian Mountains. A change in the average regional visibility means that some individual days will likely see dramatic improvements in visibility, perhaps nearly eliminating man-made impairment due to sulfate episodes. However, the current models are not reliable enough to predict the exact magnitude of specific single day events. To better ascertain events of very good visibility and very bad visibility the entire distribution of very good to very bad visibility conditions of the modeling analysis were reviewed. The estimated improvement in Eastern regional visibility are directly related to provisions of the Clean Air Act Amendments addressing control of sulfur dioxide emissions in the East.

Uncertainties in the analysis are mainly from emissions estimates of the species of pollutants that result in particles that impair regional visibility. This report only estimated emissions reductions mandated by the Clean Air Act Amendments to the extent that those emissions could be quantified. In many urban areas of the East and West, air pollution management measures may be put into effect to meet national ambient air quality standards for ozone and particulate matter that will reduce pollutants or prevent the level of growth estimated here. The effect of those programs would be to increase the regional visual air quality. Efforts in the Los Angeles area could result in perceptible improvement in regional visibility levels at class I areas in the closest class I areas. Overall, over the time horizon of this study, regional visibility should improve or remain stable across the continental U.S.

Geographically, the largest uncertainties in predicting visual air quality, particularly for the sensitive western areas, are

Figure ES-7. Class I Areas Expecting a Perceptible Improvement Cold Season Average Visibility

Average Visual Range (Oct-Mar). A 1 dv change is considered perceptible
Nearby Class I Areas should have similar changes in regional visibility as those indicated

Figure ES-8. Class I Areas Expecting a Perceptible Improvement Warm Season Average Visibility

Average Visual Range (Apr-Sep). A 1 dv change is considered perceptible
Nearby Class I Areas should have similar changes in regional visibility as those indicated..

sources of emissions from Mexico. The largest uncertainty for pollutant type is in estimates of changes in organic particle concentrations, especially those formed secondarily (in the atmosphere) from emissions (natural and man-made) of gaseous volatile organic compounds. Bounding analyses to identify plausible ranges of man-made contributions to this component of visibility impairment were preformed for the more sensitive western areas. These analyses indicated that the range of plausible changes in man-made secondary organic material would likely not result in perceptible regional visibility changes. Although visibility will improve in many eastern class I areas, based on estimates of the natural annual average visibility developed for the National Acidic Precipitation Assessment Program, there will still be perceptible man-made regional visibility impairment in all class I areas nationwide.

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Definitions

Acid precipitation - typically is rain with high concentrations of acids produced by the interaction of water with oxygenated compounds of sulfur and nitrogen which are the by-products of fossil fuel combustion.

Aerosols - gaseous suspension of ultramicroscopic particles of a liquid or a solid. Atmospheric aerosols govern variations in light extinction and, therefore, visibility reduction. Aerosol size distribution and chemistry are key parameters.

Anthropogenic - refers to alteration to the natural environment caused by human activity, i.e., man-made.

Apportionment - the act of assessing the degree to which specific components contribute to light extinction or aerosol mass.

Atmospheric clarity - is an optical property related to the visual quality of the landscape viewed from a distance (see optical depth and turbidity).

Contrast transmittance - contrast transmittance is the ratio between apparent and inherent spectral contrast. When the object is darker than its background, it has a value between 0 and -1. For objects brighter than their background, the value varies from 0 to infinity. When the contrast transmittance is equal to zero, the object cannot be seen.

Current conditions - refer to contemporary, or exiting, atmospheric conditions that are affected by human activity.

Deciview - The scale used in a haziness index designed to be linear to humanly-perceived changes in visibility caused solely by air quality changes. The deciview scale is near zero for pristine atmospheric conditions and increases as visibility degrades. The perceptibility of a change in haziness of a scene corresponding to two pollutant levels is proportional to the difference in the deciview values for those two levels. A 1 deciview (dv) change corresponds to a 10% change in light extinction, which is thought to be a small but perceptible visibility change. Larger changes in perceived haziness are indicated by greater deciview differences.

Deliquescence - the process that occurs when the vapor pressure of the saturated aqueous solution of a substance is less than the vapor pressure of water in the ambient air. Water vapor is collected until the substance is dissolved and in equilibrium with its environment.

Edge sharpness - describes a characteristic of landscape features. Landscape features with sharp edges contain scenic features with abrupt changes in brightness.

Equilibration - a balancing or counter balancing to create stability, often with a standard measure or constant.

Hydrophobic - lacking affinity for water, or failing to adsorb or absorb water.

Hygroscopic - an ability or tendency to rapidly accelerate condensation of water vapor around a nucleus. Also pertains to a substance (*e.g.*, aerosols) which have an affinity for water and whose physical characteristics are appreciably altered by the effects of water.

Koschmeider constant - the constant in the reciprocal relationship between standard visual range and the extinction coefficient (see standard visual range).

Light extinction (Extinction coefficient) - the attenuation of light per unit distance due to absorption and scattering by the gases and particles in the atmosphere.

Mie scattering - the attenuation of light in the atmosphere by scattering due to particles of a size comparable to the wavelength of the incident light. This is the phenomenon largely responsible for the reduction of atmospheric visibility. Visible solar radiation falls into the range from 0.4 to 0.8 μm, roughly, with a maximum intensity around 0.52 μm.

Natural conditions - refer to the prehistoric distribution of atmospheric states, *i.e.*, atmospheric conditions that are not affected by human activities.

Nephelometer - an instrument used to measure the light scattering component of light extinction.

Optical depth - the degree to which a cloud or haze prevents light from passing through it. It is a function of physical composition, size distribution, and particle concentration. Often used interchangeably with "turbidity".

Path radiance - or "airlight", is a radiometric property of the air resulting from light scattering processes along the sight line, or path, between a viewer and the object (target).

Primary particles - primary particles are suspended in the atmosphere as particles from the time of emission (*e.g.*, dust and soot).

Rayleigh scattering - refers to the scattering of light by air molecules, also called blue-sky scatter.

Regional haze - the haze that uniformly covers a broad (2000 to 7000 square kilometers) geographic area made up of natural and man-made components.

Secondary particles - are formed in the atmosphere by a gas-to-particle conversion process.

Standard visual range - is the reciprocal of the extinction coefficient. The distance under uniform daylight lighting conditions at which the apparent contrast between a specified target and its background becomes just equal to the threshold contrast of an observer, assumed to be 0.02.

Threshold contrast - a measure of human eye sensitivity to contrast. It is the smallest increment of contrast perceptible by the human eye.

Transmissometer - an instrument that measures atmospheric transmittance. From transmittance, the atmospheric extinction coefficient can be derived.

Transmittance - the fraction of initial light from a light source that is transmitted through the atmosphere. Light is attenuated by scattering and absorption from gases and particles.

Turbidity - a condition that reduces atmospheric transparency to radiation, especially light. The degree of cloudiness, or haziness, caused by the presence of aerosols, gases, and dust.

Visibility - refers to the visual quality of the view, or scene, in daylight with respect to color rendition and contrast definition. The ability to perceive form, color, and texture.

Visibility indexes - have been formalized for aerosol, optical, and scenic attributes. Aerosol indexes include mass concentrations, particle compositions, physical characteristics, and size distributions. The optical indexes include coefficients for scattering, extinction, and absorption. Scenic indexes comprise visual range, contrast, radiance, color, and deciview.

Visibility reduction - is the impairment or degradation of atmospheric clarity. Becomes significant when the color and contrast values of a scene to the horizon are altered or distorted by airborne impurities.

Visual air quality - Refers to the influence of air quality on atmospheric visibility. For a specific scene, changes in lighting conditions (*e.g.*, position of the sun) and the inherent appearance of the scene (*e.g.*, adding clouds or snow cover) are

important factors that influence perceived visibility. However, they are purposely held constant when evaluating visual air quality effects. Visual air quality is the only aspect of visibility addressed by the Clean Air Act.

Chapter 1. Introduction

Scope of Report

This report is in response to the requirement of Section 169B(b) of the Clean Air Act (Act). Section 169B was added to the Clean Air Act in 1990[1] as a supplement to Section 169A which established the general provisions for special protection of class I Federal areas[2] from man-made visibility impairment. Section 169B(b) requires an assessment and report to Congress on the progress and improvements expected in visibility in class I Federal areas from implementation of the provisions of the 1990 Clean Air Act Amendments (CAAA) (other than the provisions of Section 169B itself). Other parts of Section 169B focus on conducting additional visibility research and monitoring, and the formation of visibility transport regions to address "regional haze" impairment of certain class I Federal areas through commissions comprised of affected States and Federal Agencies.

In Section 169A of the Act, Congress established as a national goal "the prevention of any future, and the remedying of any existing impairment of visibility in mandatory class I Federal areas which impairment results from man-made air pollution." (95th Congress, 1977). Section 169A(a)(3) directed the EPA to write a report to Congress on methods for implementing the national goal. In 1979, the EPA issued its report (1979 Report)[3] which, among other things, reviewed the mechanisms of human perception and fundamentals of atmospheric visibility impairment and identified various types of visibility impairment. The basic science and mechanisms of visibility impairment formation are not reviewed in detail in this report. However, a brief review of the historical trends and current conditions of regional visibility impairment are provided for perspective in reviewing the estimated future conditions.

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[1] On November 15, 1990, significant amendments to the Clean Air Act were signed into law. Pub L. No. 101-549, 104 Stat. 2399. Section 816 of the 1990 Clean Air Act Amendments added section 169B to the Act. 104 Stat. at 2695-97.

[2] International Parks, National wilderness and National Memorial Parks exceeding 5,000 acres in size, and National Parks exceeding 6,000 acres as provided in section 162(a) of the Act.

[3] "Protecting Visibility, An EPA Report to Congress", U.S. EPA, Office of Air Quality Planing and Standards, October 1979, EPA-450/5-79-008

This report will focus only on regionally homogeneous haze or, more commonly, "regional haze." In this report, regional haze is defined to be uniform haze extending over a geographic area of 2000 to 7000 square kilometers. This report does not focus on layered haze events or other site specific impairments at class I areas. It is possible that reductions in air pollution resulting from the Clean Air Act Amendments of 1990 will result in improvements of visibility impairment associated with local source impacts on specific class I areas. However, without exact knowledge of specific source emissions changes and detailed reviews of the local meteorology no meaningful estimate of changes could be produced. In addition, as part of implementing existing visibility regulations, the EPA has recently concluded a regulatory review process to address visibility impairment in class I areas that is "reasonably attributable" to nearby sources of pollution. This review found few sources of such impairment based on currently available information. While new information may reveal additional instances of existing "reasonably attributable" impairment in class I areas, these will be infrequent cases. Most impairment at class I areas results from long-range transport of pollution that manifests in a regional, largely homogeneous haze.[4]

Given limited resources, this report follows the recent guidance of the National Academy of Sciences report on regional visibility by applying a simple approach to estimating visibility conditions and changes across the U.S. Then the report uses more complex estimation techniques for regions of the country that are likely to have perceptible changes in visibility resulting from changes in pollutant emissions.[5]

The Clean Air Act Amendments of 1990 and the technical analyses accompanying their development indicate that visibility improvements are expected as a corollary benefit from certain programs, notably the provisions for addressing acidic deposition. As specified in section 169B(B), this report summarizes the changes in visibility expected from implementation of the Clean Air Act Amendments of 1990 without projecting improvements resulting from actions that may be taken under section 169B.

Chapter 2 reviews the measures of visibility impairment used in this report. The measures are estimated spatially (grid cells in a modeling domain) and temporally (warm and cold seasons) to

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[4] Protecting Visibility in National Parks and Wilderness Areas, Committee on Haze in National Parks and Wilderness Areas, National Research Council, National Academy of Sciences, January, 1993, pg. 6.

[5] Ibid. pg. 7.

develop a basic understanding of the distribution of visibility changes. Chapter 3 reviews the pollutants related to visibility impairment and the trends of those pollutants and visibility impairment to lend perspective on future estimates. Chapter 4 covers a preliminary estimate of future national visibility trends. This preliminary estimate guided the allotment of resources for the air quality modeling discussed in Chapters 5 and 6. Chapter 5 reviews changes in visibility expected for the eastern U.S. This review is based on a regional model developed by the EPA for the National Acidic Precipitation Assessment Program (NAPAP). Chapter 6 reviews a modeling effort to characterize the expected change in visibility in the southwestern U.S. Chapter 7 explores the differences between the analyses for all regions of the country and explains the limitations on analyses and conclusions.

Chapter 2. Defining Visibility and Its Measures

What is "Visibility"?

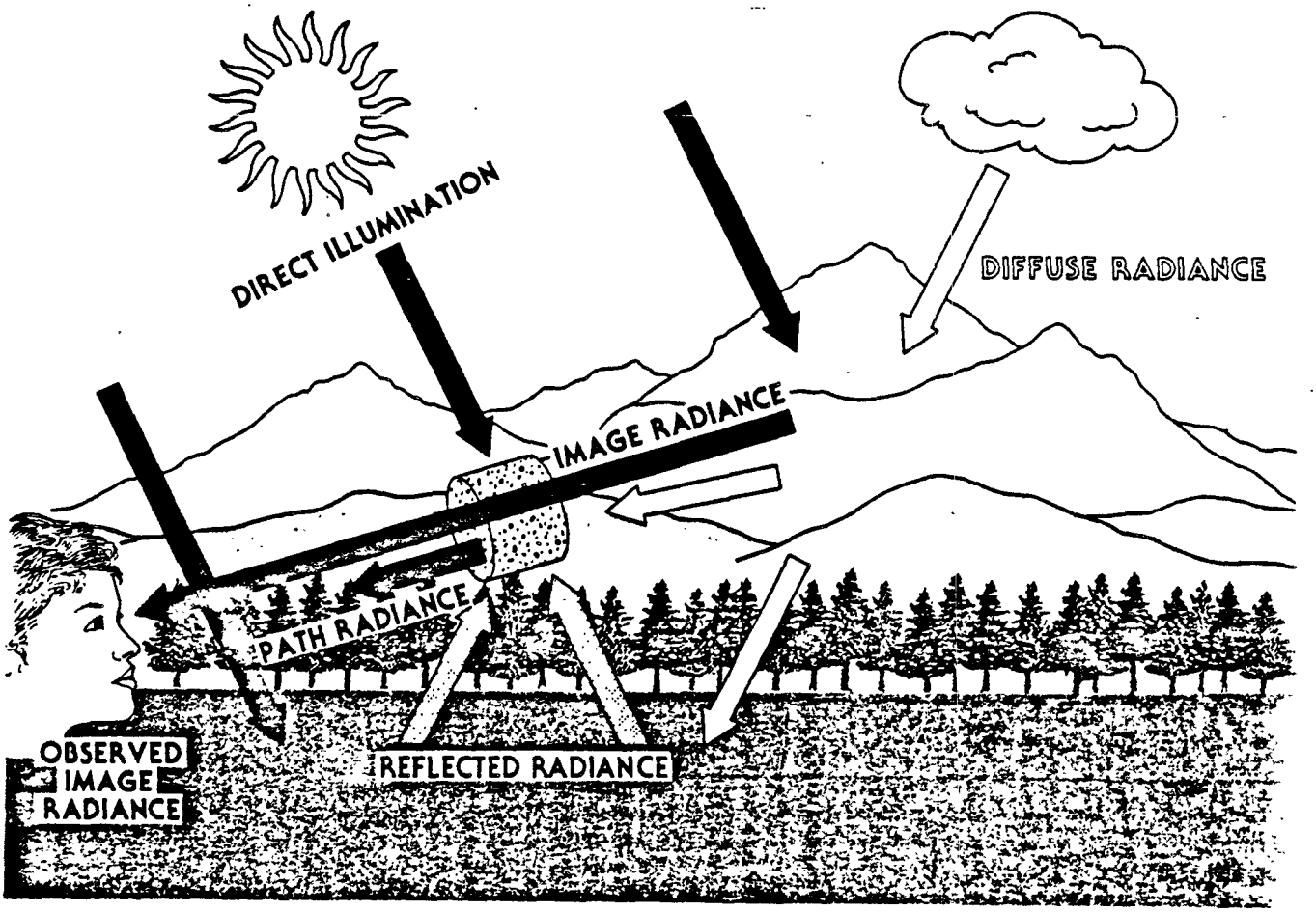
Historically, visibility has been defined in a number of ways depending on the specific application of the term. For the purpose of visibility protection in class I Areas, visibility can be defined as the effects of atmospheric constituents on the appearance of a scene viewed from a distance. However, since non-air quality factors can influence the appearance of a scene viewed from a distance, some have chosen to use the term visual air quality to more clearly specify which aspects of visibility are of interest.

For an object to be seen against a background, there must be sufficient contrast between the object and its background. That is to say that the light from the object and the background must be sufficiently different in apparent brightness or color to make the object stand out against the background. Light from objects and their background viewed through the atmosphere from a distance are modified by the constituents of the atmosphere. Figure 2-1 is a schematic of the processes involved. Light as it traverses the atmosphere is scattered (i.e., redirected in a random direction) and absorbed (i.e., converted from light to heat) by the particles and gases in the atmosphere. This affects the appearance of scenes in two ways. The image-forming light (also called image radiance) from scenic features is diminished since a fraction of the light is scattered or absorbed; non-image-forming light (also called path radiance) is scattered into the sight path. Both of these effects lower the contrast between object and background, and cause the scene to be more obscured. This contrast reduction increases with distance to the scenic feature being viewed, and with increased concentration of constituents responsible for scattering and absorbing light.

All atmospheric particles and gases scatter light and some of them absorb light. Scattering of light by gas molecules (including the nitrogen and oxygen in pure air), referred to as Rayleigh scatter, is responsible for a limit on visibility, even for an atmosphere, that has no air pollution. The only gas that absorbs visible light to any appreciable extent at concentrations expected in the atmosphere is nitrogen dioxide which absorbs preferentially in the blue resulting in a yellowish discoloration when looking through sufficient quantities of the gas. Regional concentrations of nitrogen dioxide are too low to be of concern to visibility, though in urban and combustion plumes they may be important.

Light scattering, and to a lesser degree, light absorption by suspended particles are the most important contributors to visibility degradation. The influence of particles depends on

Figure 2-1. Diagram of Visibility Concepts
(Source: NAPAP, State of Science/Technology Report #24 (1990)



Schematic diagram showing the interaction of direct and diffuse radiance with landscape features and atmospheric particles to produce image forming and path radiance.

the concentration, composition, and the size of the particles. Particles in a size range from about 0.5 to 1.0 microns diameter scatter more light for the same mass concentration than smaller or larger particle. Black carbon, primarily from incomplete combustion such as in diesel exhaust or wood smoke, is the principal cause of light absorption in the atmosphere. Some particles are composed of materials such as sulfates and nitrates that cause water vapor from the air to form solution drops under high relative humidity condition. Since the solution drops are larger than the dry particles, visibility impairment by these particles increases during high humidity conditions.

Non-visual air quality factors such as lighting conditions and inherent appearance of the scene, also have an influence on the appearance of the scene viewed at a distance. For example, the position of the sun with respect to the viewing angle of the scene and characteristics of the clouds, if any, determines the nature of shadows in the scene and influences the amount of non-image-forming light. Also, visibility is usually dramatically reduced during periods of precipitation and fog. Since factors of this type are continually changing and are generally unpredictable, they can not be made a part of a predictive analysis of visibility effects. However, these non-air quality factors are assumed to have the same influence when averaged over sufficient time and space so that they do not need to be separately evaluated for this report.

Unlike the nearly constant Rayleigh contribution to visibility impairment, the contribution by particles from both natural and man-made processes are highly variable. Natural particle sources such as wildfires, windblown dust, salts from ocean spray, fog and precipitation, etc. are highly variable across time and space with the result that natural background levels of visibility are highly variable. Concentrations of man-made and natural particles also vary because of the influence of variable meteorology responsible for atmospheric transport and dispersion. Estimates of the eastern and western regional annual averaged natural background visibility levels (Rayleigh scattering plus contributions by natural particle sources) have been made using particulate composition data and emission source inventories. The difference between annual averaged current conditions and the estimated natural background contributions to visibility impairment is an estimate of the averaged man-made contribution to visibility impairment.

For further information on visibility, see the 1979 Report and the 1990 NAPAP Report "Acidic Deposition: State of Science and Technology, Volume III, Report Number 24, entitled Visibility: Existing and Historical Conditions - Causes and Effects.

Visibility Metrics

Visual range, which is defined as the greatest distance that a large dark object can be seen against the background sky, is the oldest and most commonly used visibility metric. Visual range was developed and continues to function well as an aid in military operations and transportation safety. Airport observations of visual range have been made since 1919, and have been computer archived since the late 1940's. Daylight observations involve viewing preselected visibility markers (large dark objects) at known distances from the observation point to determine the most distant marker that is visible. At night, lights are used instead of markers. One of the more serious shortcomings of airport observations of visual range is the availability of suitable targets at reasonable distances. It is not unusual for the actual visual range to be greater than the most distant target.

In spite of such difficulty, visual range is likely to remain a popular measure of visibility because of its familiar distance units (kilometers or miles), simple definition, and the fact that any sighted person can use it to characterize visual conditions without instrumentation. These very attributes which make visual range popular also result in its common misinterpretation. For example, some people mistakenly believe that all objects out to a distance of the visual range are clearly seen and therefore visibility is unimpaired as long as the visual range is greater than the distance to the furthest scenic feature of interest. In fact, noticeable degradation of scenic appearance including the disappearance of some features is likely for objects as near as 10% of the visual range.

Another traditional visibility metric is extinction coefficient, which is the attenuation of light per unit distance due to scattering and absorption by gases and particle in the atmosphere. Extinction coefficient is expressed in inverse length units (e.g., km^{-1}) and is used primarily by scientists studying the causes of reduced visibility. Direct relationships exist between concentrations of atmospheric constituents and their contribution to extinction coefficient. Apportioning extinction coefficient to atmospheric constituents provides a method to estimate change in visibility caused by change in constituent concentrations. Calculation of the extinction coefficients corresponding to air quality model predicted pollutant concentrations is the approach used in the analyses done for this report in order to estimate the visibility changes expected to result from Clean Air Act mandated emission changes. An estimate of visual range, commonly termed standard visual range, can be made from extinction coefficient using a simple transformation known as Koschmieder's relationship. The visual

range values in this report are calculated from predicted or measured extinction coefficient values.

Neither visual range nor extinction coefficient is linear to perceived visual changes caused by uniform haze. For example, a 5km change in visual range or a $0.01km^{-1}$ change in extinction coefficient can result in a scene change that is either imperceptible or very obvious, depending on the baseline visibility conditions. Presentation of visibility data or model results in terms of visual range or extinction coefficient creates the potential for misinterpretation by those who are not aware of the non-linear relationship, and requires the inconveniences of further analysis for those who are aware.

To avoid these difficulties, a new visibility index related to perception of atmospheric haze was recently developed.[1] The scale of this visibility index, expressed in deciview (dv), was designed to be linear with respect to perceived visibility changes over its entire range, analogous to the decibel scale for sound. A one dv change is approximately a 10% change in the extinction coefficient, which is a small but usually perceptible scenic change. The deciview scale is near zero for a pristine atmosphere (Rayleigh conditions) and increases as visibility impairment increases. Because the index increases as haze increases, it is characterized as a haziness index. The deciview scale is defined in terms of the logarithm of the extinction coefficient, allowing simple transformations between all of the common visibility metrics. Since the deciview scale is perceptually linear, a change of any specific number of dv should appear to have approximately the same magnitude of visual change on any scene regardless of baseline visibility conditions.

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[1] Pitchford, M.L. and Malm, W.C. (1992) Development and Applications of a Standard Visual Index, Presented at the Conference on Visibility and Fine Particles, Vienna, Austria. Accepted for publication by *Atmospheric Environment*, in 1993.

Chapter 3. Historical Perspective and Current Conditions

Trends of Visibility

Figure 3-1 shows the location of the 158 mandatory class I Federal areas. Prior to routine instrument-based monitoring of visibility conditions begun in 1978, the National Weather Service (NWS) observations are the only data available to track visibility changes. Figure 3-2 indicates the trend of the NWS observations across the country. (NAPAP 24-30) From this analysis, visibility is noted to improve in the northeast during the winter, and decline in the east in general and the southeast in particular in the summer. Western rural values show little change according to the NWS data likely due to higher visibility levels and a less dense network of data collection.

Monitoring of visibility conditions specifically in class I areas was begun in 1978, with emphasis on the western areas. Starting in 1987, to fulfill requirements for monitoring under the EPA's visibility regulations, a multi-agency monitoring system began operation in approximately 30 class I areas. Monitoring of other class I areas, using similar techniques, takes place in approximately 13 more class I areas. Limited analysis of these data have taken place. One study of data from the southwestern monitoring sites indicates improved summer visibility, but winter visibility has remained constant between 1988 and 1991.[1]

Current Conditions at Class I Areas

Monitoring of class I areas through the Inter-agency Monitoring of Protected Visual Environments (IMPROVE) network provides information to develop current visibility conditions at class I areas across the U.S. Figure 3-3 illustrates current visibility annual average conditions at selected class I areas based on IMPROVE data. The IMPROVE estimates of current visibility are based on reconstructing the components of visibility impairment, including Rayleigh and natural aerosols. Results of two reconstruction techniques are shown in Table 3-1 along with the measured visibility impairment. Techniques to estimate visibility conditions for an annual or seasonal time period generally compare well (within 10 percent) with measured atmospheric conditions in the East, Central Rockies and Colorado Plateau. Reconstructed extinction is typically 70-80 percent of the measured extinction. The worst agreement is in the Sierra Nevada (Yosemite National Park monitor) where the reconstructed

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[1] Visual Air Quality in the Grand Canyon and Golden Circle: An Assessment of Measurements, Source Contributions, and Trends, D.A. Latimer, AWMA 86th Annual Meeting, Paper 93-MP-4.09

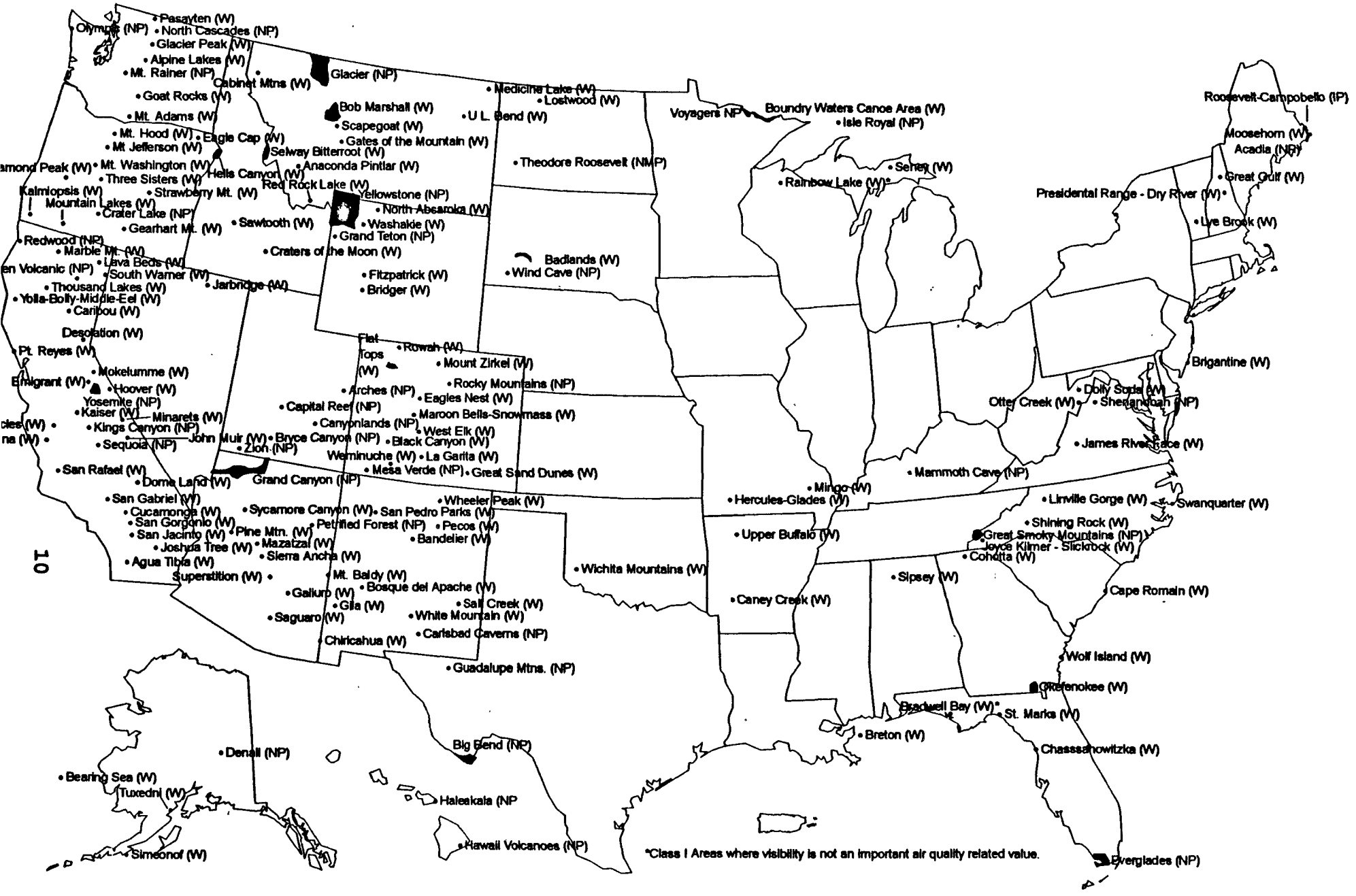
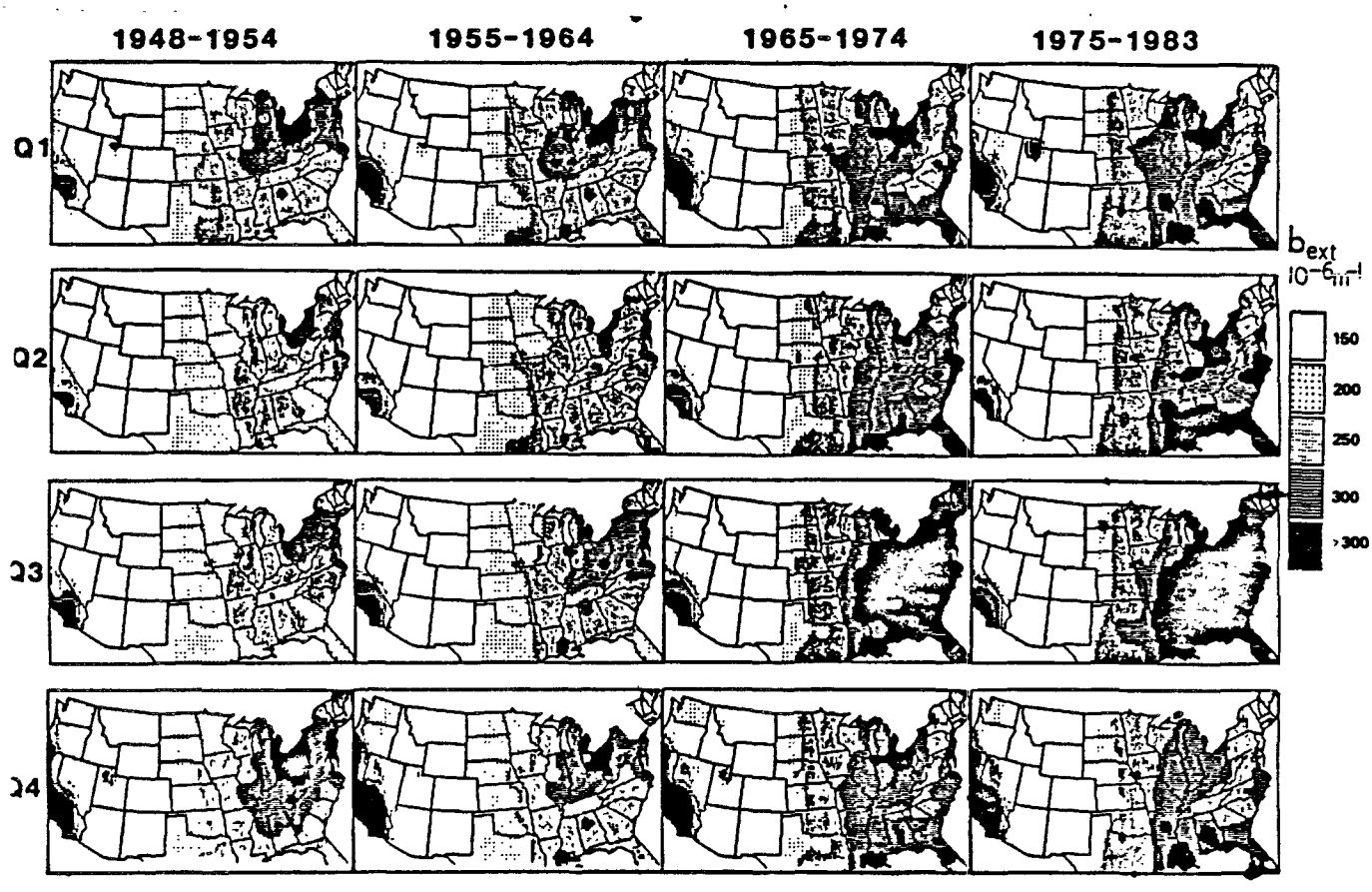


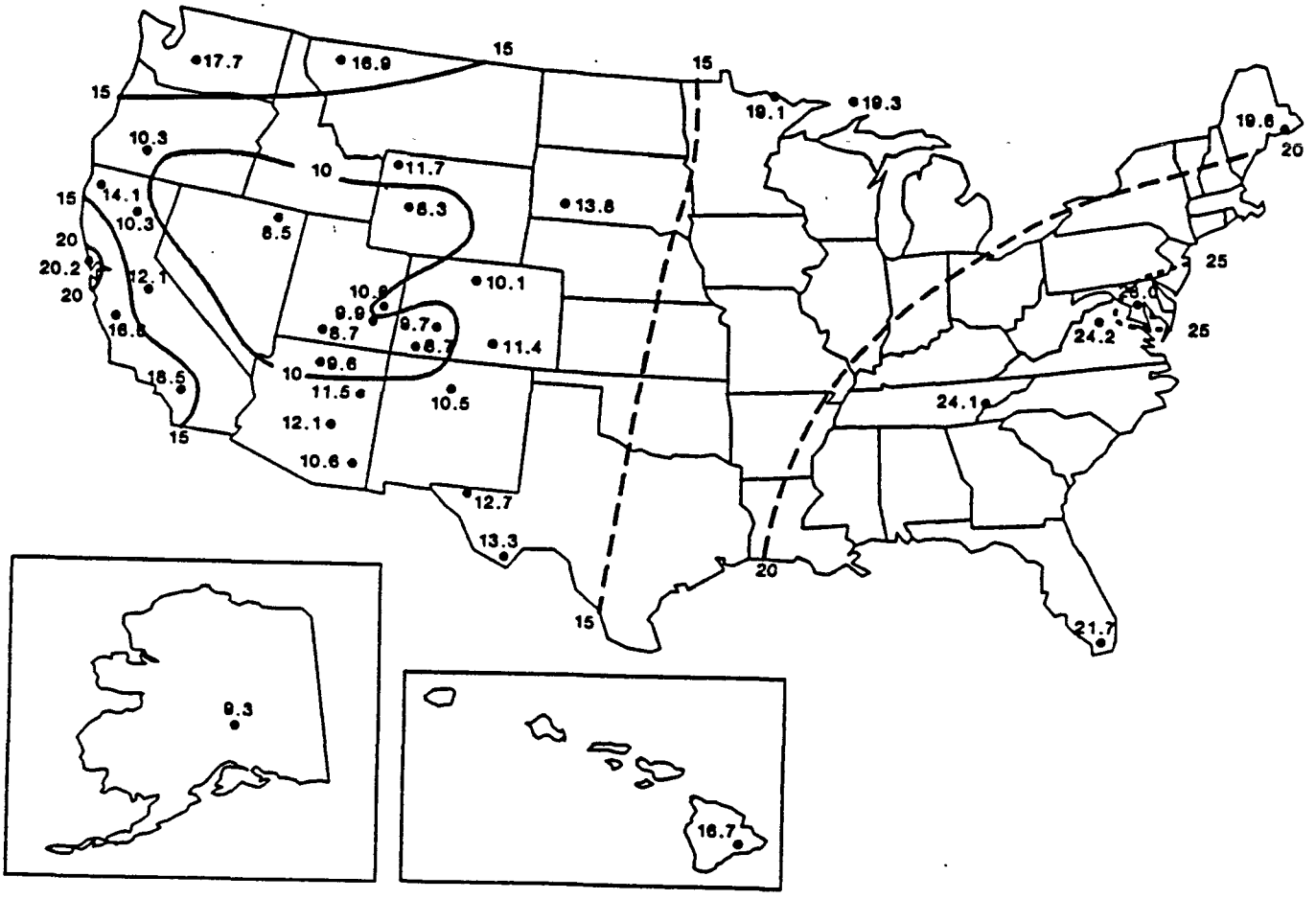
Figure 3-1. Map of Mandatory Federal Class I Areas

Figure 3-2. National Weather Service Visibility Trends
(Source: NAPAP, State of Science/Technology, Report #24, 1990)



United States trend maps for the 75th percentile extinction coefficient (derived from air visual range data) for the calendrical quarters: winter (Q1), spring (Q2), summer (Q3), and fall (Q4).

Figure 3-3. Average Visibility (deciview) at Selected Monitored Class I Areas (1988-1991)
(Source: IMPROVE, CIRA Report, Feb. 1993)



Average visibility impairment in deciviews calculated from total (Rayleigh included) reconstructed light extinction for the first three years of IMPROVE, March 1988 through February 1991.

Table 3-1. Comparison of Measured and Reconstructed Visual Range (IMPROVE March 1988-1991)
(Source: IMPROVE, CIRA Report, Feb. 1993)

IMPROVE Region	Measured Annual Average Visual Range (km)	Reconstructed Annual Average Visual Range (km) (Dry Organics)	Reconstructed Annual Average Visual Range (km) (50% of Organics Assumed Hygroscopic)
Appalachian	32	36	34
Colorado Plateau	145	151	149
Central Rockies	165	167	164
Pacific Coast	78	98	97
Northeast	96	94	91
Northern Great Plains	120	127	123
Northern Rockies	84	103	95
Southern California	49	64	63
Sonoran Desert	105	135	134
Sierra Nevada	66	133	131
West Texas	89	124	123

extinction is only 50% of the measured value. This may be due to the fact that the aerosol monitor is located above the mixed layer much of the time. For this report, reconstructed extinction will be used to estimate changes in future conditions. The baseline extinction of the models was adjusted for measured extinction levels.

Causes of Current Visibility Conditions

As noted before, regional visibility conditions are dominated by a continuously varying mix of natural and man-made fine particles in the troposphere. Many studies have been published on visibility conditions and related aerosol concentrations. The NAPAP lists 33 aerosol and visibility databases. From these studies, the major contributors to visibility impairment from natural and man-made sources are sulfate particles, organic particles, elemental carbon, suspended dust, nitrate particles, and nitrogen dioxide. The National Academy of Sciences (NAS) developed an estimate of regional man-made contributions of these categories for three regions of the country that contain 90 percent of the class I areas. These regions are the East (states east of the Mississippi River), the Southwest (California, Nevada, Arizona, New Mexico, Utah, and Colorado), and the Pacific Northwest (Oregon, Washington, and Idaho). Table 3-2 summarizes the NAS model results.

The EPA's estimate of changes in visibility in the class I areas focuses on estimating changes in these identified categories of particles. The contribution of nitrogen dioxide to light is very small, particularly in and near the remote class I areas, and, therefore, is not considered in development of future cases as a direct cause of regional impairment. Regional nitrogen dioxide emissions and their resulting conversion to nitrate particles is considered. The primary pollutant emissions that lead to formation of the identified components of regional man-made visibility impairment reviewed in this report are sulfur dioxide, oxides of nitrogen, primary organics and primary particulate matter.

IMPROVE monitoring data were used to establish annual and seasonal apportionment of current aerosol components to the total visibility impairment for specific class I areas. An example of the IMPROVE data for annual averages is given in Table 3-4.

Table 3-2. Anthropogenic Visibility (Extinction) Budgets by Rural Regions of the Country[a]

(Source: Protecting Visibility in National Parks and Wilderness Areas, National Research Council, National Academy Press, 1993)

	East[b]	Southwest[c]	Northwest[d]
Sulfates	65	39	33
Organics	14	18	28
Elemental carbon	11	14	15
Suspended dust	2	15	7
Nitrates	5	9	13
Nitrogen dioxide	3	5	4

[a]Percentage contribution by specific pollutant to anthropogenic light extinction in three regions of the United States.

[b]Based on Table 9, Table 18, Figure 45, Appendix A, and Appendix E of NAPAP Visibility SOS/T Report (Trijonis et al., 1990). It is assumed that sulfates (3% natural) account for 60% of non-Rayleigh extinction, organics (33% natural) account for 18%, elemental carbon (3% natural) accounts for 10%, suspended dust (50% natural) accounts for 4%, nitrates (10% natural) account for 5%, and nitrogen dioxide (10% natural) accounts for 3%.

[c]Based on Table 9, Table 18, Figure 45, Appendix A, and Appendix E of the NAPAP Visibility SOS/T Report (Trijonis et al., 1990). It is assumed that sulfates (10% natural) account for 33% of non-Rayleigh extinction, organics (33% natural) account for 20%, elemental carbon (10% natural) accounts for 12%, suspended dust (50% natural) accounts for 23%, nitrates (10% natural) account for 8%, and nitrogen dioxide (10% natural) accounts for 4%.

[d]Extinction efficiencies (relative to organics) are chosen as 1.5 for sulfates, 2.5 for elemental carbon, 0.3 for fine crustal materials, and 1.5 for nitrates (Trijonis et al., 1988, 1990). Coarse dust extinction is assumed to be three times fine dust extinction (Trijonis et al., 1988, 1990). Natural aerosol particle fractions are assumed to be one-tenth for sulfates, one-third for organics, one-tenth for elemental carbon, one-half for crustal materials, and one-tenth for nitrates. These assumptions are applied using the fine mass concentrations in Trijonis et al., (1990). The percentage contribution for nitrogen dioxide is assumed to be 4%.

Table 3-3. Annual Averages (March 1988-February 1991) of Reconstructed Light Extinction (Mm^{-1}) for 19 Regions of the IMPROVE Network.
(Source: IMPROVE, CIRA Report, Feb. 1993)

REGION	Total Extinction	Aerosol Extinction	Sulfate	Nitrate	Organics	Elemental carbon	Soil and Coarse
ALASKA	25.4	15.4	6.7	0.7	4.6	0.5	2.6
APPALACHIAN	112.2	102.2	69.7	6.9	16.7	4.6	4.3
BOUNDARY WATERS	68.2	58.2	29.8	8.4	14.1	2.2	3.8
CASCADES	58.8	48.8	19.0	3.3	19.2	4.9	2.4
CENTRAL ROCKIES	28.1	18.8	5.8	1.3	6.1	1.3	3.6
CENTRAL CALIFORNIA COAST	56.3	46.3	15.4	12.1	10.6	2.7	5.6
COLORADO PLATEAU	27.1	17.1	6.0	1.4	4.7	1.5	3.5
FLORIDA	87.5	77.5	42.4	9.5	15.4	3.6	6.7
GREAT BASIN	23.4	13.4	3.4	0.9	4.6	0.6	4.0
HAWAII	53.2	43.2	31.5	1.0	5.0	0.7	5.1
NORTHEAST	71.3	61.3	38.3	5.1	11.0	4.0	2.9
NORTHERN GREAT PLAINS	39.7	29.7	13.1	3.3	7.3	1.4	4.7
NORTHERN ROCKIES	54.3	44.3	12.4	4.0	19.6	4.3	3.9
SIERRA NEVADA	33.4	24.4	5.7	3.6	8.1	2.5	3.4
SIERRA HUMBOLDT	28.0	18.0	4.4	1.4	7.7	1.8	2.7
SONORAN DESERT	31.3	21.3	8.1	1.3	5.5	1.8	4.5
SOUTHERN CALIFORNIA	63.5	53.5	7.7	23.8	9.7	4.8	7.5
WASHINGTON, D.C.	164.3	154.3	75.6	24.6	25.0	18.4	10.6
WEST TEXAS	36.7	26.7	12.2	1.4	5.7	1.5	5.9

Chapter 4. Preliminary Estimation of Future Conditions

In order to estimate the effects on visibility due to emissions changes expected to occur as a result of implementation of the CAAA, it was necessary to predict the changes in pollutant concentrations for those species that are most important to visibility degradation. In the East, sulfates predominate the man-made visibility degradation. The estimates of visibility change address changes in sulfur dioxide emissions and nitrogen dioxide emissions. Changes in man-made volatile organic compounds in the East are driven by air quality control measures to attain the ozone health standard. These occur primarily in urban areas, particularly in the northeast. In the southwest, it was determined that the modeling exercise should include sulfates, nitrates, primary carbonaceous particles (organic and elemental), and remaining fine particle mass. Although secondary organics are sometimes a large portion of the ambient organic particulate matter in rural atmospheres, it is not clear whether these rural concentrations are anthropogenic or natural in origin. For analysis purposes, the secondary organic particulate matter effects on visibility are reviewed as a sensitivity analysis on the eastern and southwestern modeling analyses. Modeling only primary anthropogenic organic material eliminated the need to prepare base and CAAA-controlled volatile organic compound (VOC) emissions inventories, and this resulted in a considerable savings in labor and computing resources.

1990 Clean Air Act Amendments

With the passage of the CAAA on November 15, 1990, the U.S. EPA was given a mandate to control air pollution using a variety of innovative new approaches. The breadth of this new mandate poses significant new regulatory and analytical requirements for states and air pollution sources located within them.

Each of the Titles of the CAAA has been reviewed to identify provisions that may affect visibility in class I areas. The focus is on provisions which will directly affect emissions of visibility-related pollutant species. A discussion of important provisions in each Title follows. Subsequently, the methodologies for quantifying emission reductions and determining the effects on visibility are presented.

The Clean Air Act as amended by the CAAA will continue to require attainment and maintenance of the national ambient air quality standards through state implementation plans (SIPs). The CAAA, however, outline a number of changes in the SIP process and new requirements in SIP submittals. Title I of the CAAA addresses areas that are not in attainment of the national ambient air quality standards for criteria pollutants, including ozone.

Title I expands the boundaries of nonattainment areas to include the entire Consolidated Metropolitan Statistical Area (CMSA). This means previously unregulated sources will have to comply with the new requirements of the CAAA. The CAAA include 'reasonable further progress' requirements which call for 15 percent VOC reductions by 1996 and additional reductions of three percent per year after that until attainment is achieved. In certain cases, NO_x reductions may be substituted for VOC reductions in order to meet the three percent per year reduction requirement. The reductions must be taken mainly by stationary sources; specific program mandated emissions reductions for motor vehicle sources are covered in Title II. NO_x emissions controls are also required for some sources. This is the first time NO_x controls have been required nation-wide for stationary sources. Previously VOC control was considered sufficient to bring areas into attainment with ozone standards. It is also the first time that quantified emissions reductions targets have been specified for such areas.

New planning requirements will have a direct impact on emissions. For example, SIPs must include enforceable emission limitations and other control measures or techniques (including economic incentives such as fees, marketable permits, and auctions of emission rights). Also, SIPs must include provisions that prohibit any activity from emitting pollutants that will contribute significantly to nonattainment in another state or that will interfere with measures required to prevent significant deterioration of ambient conditions.

Under the particulate matter provisions within Title I, Reasonably Available Control Measures (RACMs) are to be implemented by December 10, 1993 in those moderate nonattainment areas (as defined in Title I); Best Available Control Measures (BACMs) must be implemented in current serious nonattainment areas by February 8, 1997 (within 4 years of reclassification). In those serious nonattainment areas failing to reach attainment by December 31, 2001, 5 percent annual PM_{10} or PM_{10} precursor emission reductions will be required.

Title II of the CAAA addresses mobile source-related emissions. Among its provisions are requirements for: (1) tighter emission standards on motor vehicles; (2) longer warranty periods on certain motor vehicle emission control equipment; (3) fuel producers to produce and sell reformulated/oxygenated gasolines which meet specific physical and compositional requirements including reduced vehicle emissions of VOCs; (4) gasoline content, such as reduced volatility, inclusion of detergents, and no lead; (5) fleet operators to purchase clean-fuel vehicles, and (6) a pilot program in the State of California to demonstrate the effectiveness of clean-fuel vehicles in controlling air pollution in ozone nonattainment areas.

The air toxics provisions in Title III of the CAAA will require reductions in hazardous air pollutants, including carcinogenic chemicals. Many of these hazardous air pollutants are volatile organic compounds (VOCs), and some are particles. Reduction in VOCs that are both toxic compounds and photochemically reactive is likely to result in some changes in visibility. Similarly, reductions in particulate matter that come about as a result of air toxics emissions rules may also affect visibility. Although reactive VOCs contribute to ozone formation and thus affect visibility, it is expected that the reductions resulting from Title III regulations will not be significant in comparison to controls implemented via Title I of the CAAA. Similarly, the majority of particulate emissions will be controlled under Title I and other provisions of the CAAA.

Provisions in Title IV of the CAAA call for large reductions in NO_x and SO_x emissions from utility power plants. Nationally, SO_x emissions are expected to be reduced by 10 million tons per year (TPY) and NO_x emissions by approximately 2 million TPY as a result of Title IV and other CAAA provisions. Since NO_x and SO_x emissions play an important role in visibility, these emission reductions have the potential for producing significant visibility improvements in at least some class I areas.

Under Title IV, power plant emissions are to be reduced in a two phase process. The second phase is scheduled to begin in the year 2000 at which time annual SO_2 emissions from all units with capacities in excess of 25 megawatts (MW) are to be reduced to a rate equal to 1.2 lb SO_2 / MMBtu times their 1985 - '87 average annual fuel consumption. In addition, units operating at less than 1.2 lb SO_2 / MMBtu before 2000 may not increase emissions by more than 20 percent. To achieve these emission reductions at the lowest possible cost, a system of marketable emission credits will be established. Thus, some sources may choose to buy credits rather than reduce emissions. A series of bonus and incentive allowances will be provided to assist midwestern sources in achieving the required emission reductions, to allow for growth in states with average emissions below 0.8 lb SO_2 / MMBtu and at sources experiencing increased utilization, and as an incentive for installing flue gas desulfurization (FGD) systems, implementing conservation programs and increasing use of renewable energy sources.

Title IV also calls for the implementation of more stringent NO_x controls. By 2000, most boilers affected by the SO_2 reduction requirements of Title IV must meet EPA-established performance standards. In addition, a revised New Source Performance Standard (NSPS) for NO_x is to be issued.

Title V of the CAAA requires states to issue operating permits for major stationary sources, including major sources subject to

air toxics regulations. The purpose of the operating permit is to allow a single document to list all the operating requirements and emission limitations that apply to a particular source. This means that conditions from prevention of significant deterioration (PSD) and other emission limits imposed by the SIP must be contained in one central document. It is unlikely that implementation of the Title V permit program will result in significant changes in emissions, since best available retrofit technology (BART)[1] and other substantive requirements are already imposed through various regulatory mechanisms. The operating permit may increase the efficiency of enforcement, but this is difficult to measure in terms of emission reduction and visibility improvement.

Provisions in Title VI of the CAAA are designed to protect the stratospheric ozone layer which has been damaged by the emissions and migration into the stratosphere of very slowly reactive clorofluorocarbon (CFC) species. The presence of CFCs in the lower atmosphere does not affect visibility. If the use of CFCs are replaced by other, more reactive, hydrocarbon species, then it is possible that, while reducing stratospheric ozone depletion, there is a potential for increased ozone formation near the surface. However, it is expected that the provisions of Title VI will add no additional controls relevant to visibility in class I areas that have not been addressed by other titles (e.g., Title I).

Title VII of the CAAA addresses issues concerning provisions for enforcement of regulatory measures. Although enforcement provisions are necessary for the realization of emission reductions, these reductions have been specified in other Titles of the CAAA. This Title does not directly stipulate emission reductions so there is no measurable effect on visibility in class I areas.

Title VIII of the CAAA addresses miscellaneous issues such as provisions for limiting emissions from outer continental shelf (OCS) development, future visibility studies to be undertaken, and authority for discounting emissions emanating from outside the U.S. for certain SIP purposes in international border areas, and establishment of a program to monitor and improve air quality in regions along the border between the U.S. and Mexico. Although the outcome of some of these provisions may lead to development and implementation of control measures, it was not possible to estimate emission reductions so no attempt was made

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[1] BART applies to certain existing major stationary sources that emit any air pollutant which may reasonably be anticipated to cause or contribute to any visibility impairment in a mandatory class I Federal area for which visibility is an important value. (See section 169A(b)(2)(A) of the Clean Air Act.

to assess the effect that Title VIII provisions will have on class I area visibility. The requirements for this report specifically exclude from consideration any programs enacted under Section 169B.

Identification of Key 1990 CAAA Provisions

Each title of the 1990 CAAA was reviewed to identify provisions that may effect visibility in class I areas. Results of this review process are summarized in Table 4-1. Provisions which do not contain specific, quantifiable emission limits were dropped from consideration, even though it could be argued that some of these provisions may result in some emission reductions. This includes the permitting provisions in Title V, the enforcement provisions in Title VII, and the miscellaneous provisions in Title VIII (including the OCS source provisions and the Mexico/Canada border provisions). Since it was determined at the outset that secondary anthropogenic organics are not as major a component of the extinction budget as sulfur and elemental carbon in most of the class I areas considered, provisions relating to VOC emissions reductions were not directly addressed in air quality modelling, although the effect of these provisions on ambient ozone levels were included in the modeling analysis for the southwestern U.S. A bounding exercise was also undertaken to establish an upper limit on visibility improvements expected to result from reductions in secondary anthropogenic organic aerosols.

Of the provisions addressed in this study, those in Title I are responsible for most of the controls on stationary source NO_x and particulate matter (PM) emissions in ozone, CO, and PM_{10} non-attainment areas. Utility NO_x and SO_2 emissions are controlled by Title IV provisions. Mobile source emission reductions arise from both Title I and Title II requirements. Although the air toxics provisions in Title III may result in some reductions of primary particulate matter emissions, these reductions are extremely difficult to quantify at this point and were therefore not included in the analysis.

Preliminary Analysis of Visibility Changes in the Federal Class I Areas

A preliminary assessment was conducted to establish the geographic region selection and classification of class I areas and to provide a qualitative estimate of the expected changes in visibility due to the CAAA. Statewide emission reduction estimates corresponding to the CAAA provisions were used to scale ambient concentrations (i.e., source category rollback) and approximate the changes in visibility-related pollutant concentrations and visual range at all class I areas in the U.S.

Table 4-1. NO_x, SO_x, and TSP Emission Control Provisions Contained in 1990 CAAA.

Title	Attainment Status of Affected Areas	Provision	Methodology for Addressing Requirement
I	Ozone: Marginal and above	Stationary sources must perform new source review (NSR) on all new and modified major sources.	Not addressed
I	Ozone: Moderate and above	Stationary sources must apply reasonably available control technology (RACT) to all major sources of VOC and NOx.	Applied RACT NO_x control factors as shown in Table 5-1
I	Ozone: Serious and above	Stationary sources must demonstrate 3% per year reduction in VOC emissions averaged over 3 year period, beginning Nov. 1996. Alternatively, provide for reductions in VOC and NOx that result in ozone reductions at least equivalent to those that would result from 3% per year reduction in VOC alone.	Not addressed (expected NO_x reductions, if any, unknown at this time)
I	Ozone: All	New CTGs requiring RACT for VOC emissions from application of aerospace coatings and solvents. VOC emissions from removal or application of paints, coatings, and solvents used in shipbuilding and repair	Not addressed (PM_{10} contributions from affected sources are minor)
I	PM-10	Reasonably available control measures (RACM) and best available control measures (BACM--including BACT) on fugitive dust, residential wood burning, prescribed burning, and other sources of PM-10	Addressed indirectly - see text
I	Ozone Transport Regions	Enhanced vehicle inspection and maintenance programs for mobile sources, existing and new CTGs, RACT for 50 tpy VOC sources and 100 tpy NO_x sources	Applied to RACT NO_x sources using control factors shown in Table 5-1
I	Ozone: Serious and above CO: Moderate (>12.7ppm) and above	Mobile sources: Enhanced vehicle inspection and maintenance programs to reduce emissions in urban areas of 200,000 people or more, by Nov. 1992.	Modeled with MOBILE 5.0
I&II	Ozone: Serious and above	Mobile sources: Implement clean fuel vehicle fleet program by May 1994, specifying a certain percentage of new fleet vehicles to use clean fuel (30% light duty and 50% heavy duty vehicles in 1998).	Not addressed (MOBILE 5.0 models only HC benefits for clean fuels)
I	Ozone: Severe and above CO: Serious	Mobile sources: Implement transportation control measures to offset growth in emissions from increased vehicle miles travelled (VMT) and to achieve emission reductions necessary for compliance, by Nov. 1992.	Not addressed (TCM effects on emissions either minor or unknown at this time)

Table 4-1. Concluded.

Title	Area Attainment Status	Description of Requirement	Methodology for Addressing Requirement
I&II	Ozone: Severe and above CO: Serious	Mobile sources: By Nov. 1992, require employers of 100+ to increase passenger occupancy per vehicle during peak hours by 25%. Reformulated gasoline for 9 worst ozone areas with population greater than 250,000 and ozone areas reclassified severe.	Not addressed - effects on total emissions expected to be generally small
I&II	All	Onboard Vehicle Controls, Reid Vapor Pressure programs.	Not addressed - effect on total emissions expected to be small
II	All	1995 reduced tailpipe NO_x emission standards	Modeled with MOBILE 5.0
I&II	CO: Moderate and above	Mobile sources: Require at least 2.7% oxygen in any gasoline sold in nonattainment area during season of high CO concentrations, beginning Oct. 1993. Fuels with higher oxygen content can be used to offset those with lower content.	Modeled with MOBILE 5.0, for all episode months
III	All Areas	Provisions related to the emissions of air toxics.	Not addressed
IV	All Areas	By 2000, most utilities must meet Phase II total SO_x emission limits and may participate in the SO_x allowance trading system	Based on CEUM results from ICF Resources for "EPA RIA low trading case"
IV	All Areas	Reduced NO_x emission factor limits for utility boilers subject to Phase I and Phase II SO_x controls; similar implementation schedule as Phase I and II SO_x allowances.	Application of Phase II emission factor limits by boiler type
V	All Areas	Increased permitting for a variety of sources. Permit enforcement provisions.	Not addressed
VI	All Areas	Stratospheric ozone protection.	Not addressed
VII	All Areas	Federal enforcement provisions.	Not addressed
VIII	All Areas	Miscellaneous provisions: off-shore emissions	Not addressed

Table 4-2 lists the 158 mandatory Federal class I areas. Figure 4-1 shows the location of each class I area as well as the regional grouping used for the preliminary analysis. For each geographical group, one or two class I areas were selected to characterize the current aerosol/extinction conditions for all other class I areas in the group. In most cases, a single class I area was considered sufficient to represent the group; however, two class I areas were used to represent geographically larger groups, and those groups containing class I areas with larger variations in aerosol mixtures.

Annual average concentrations of the major fine particle (less than 2.5 μm) constituents (sulfate, nitrate, organic and elemental carbon, and soil dust) for the selected class I areas were extracted from the National Park Service (NPS) air monitoring network data collected during 1983-1986.

Average extinction resulting from each of five fine mass components was determined by multiplying each average species concentration by an individual extinction efficiency based on literature review. A simple functional form for sulfate and nitrate humidity-dependent extinction efficiency was used to approximate the deliquescent nature of sulfate and nitrate particles. Annual mean daytime relative humidity from the nearest major city was used for each representative class I area. Average extinction for NO_2 and coarse mass were also taken from the literature.

Extinction for the anthropogenic portion of the five fine particle species, coarse mass, and NO_2 was determined by subtracting an estimated natural background extinction from the total extinction estimate. Background values for SO_4, NO_3, and elemental carbon were based on the NAPAP. Natural extinction for organic carbon was assumed to be 75 percent of the total organic carbon in rural areas, and 25 percent near urban areas. All extinction from coarse mass and fine mass soil dust was assumed to be natural sources. All extinction from NO_2 was assumed anthropogenic.

The contribution of each source category to atmospheric fine mass component concentrations was approximated using the relative emission strength for the source category. Ambient concentrations (anthropogenic portion) of sulfate, nitrate (and NO_2), elemental carbon, primary organic carbon, and secondary organic carbon were assumed to be directly related to emission rates of sulfur dioxide, nitrogen oxides, soot, organic carbon and volatile organic carbon, respectively. Relative percent contributions of each source category from upwind states were combined via a weighted sum of emission loadings. The estimated source attributions were tabulated as a matrix displaying the

Table 4-2. List of Mandatory Federal Class I Areas

Class I Area	Group Number	Class I Area Name/location
1	1	Pasayten W, WA
2	1	North Cascades NP, WA
3	1	Glacier Peak W, WA
4	1	Alpine Lakes W, WA
5	2	Olympic NP, WA
6	1	Mount Rainer NP, WA
7	1	Goat Rocks W, WA
8	1	Mount Adams W, WA
9	1	Mount Hood W, OR
10	3	Eagle Cap W, OR
11	3	Hells Canyon W, OR,ID
12	3	Strawberry Mountain W, OR
13	1	Mount Jefferson W, OR
14	1	Mount Washington W, OR
15	1	Three Sisters W, OR
16	1	Diamond Peak W, OR
17	1	Crater Lake NP, OR
18	1	Gearhart Mountain W, OR
19	1	Mountain Lakes W, OR
20	2	Kalmiopsis W, OR
21	2	Redwood NP, CA
22	2	Marble Mountain W, CA
23	1	Lava Beds W, CA
24	1	South Warner W, CA
25	1	Thousand Lakes W, CA
26	2	Yolla-Bolly-Middle-Eel W, CA
27	1	Lassen Volcanic NP, CA
28	1	Caribou W, CA
29	5	Desolation W, CA
30	5	Mokelumne W, CA
31	4	Point Reyes W, CA
32	5	Emigrant W, CA
33	5	Yosemite NP, CA
34	5	Hoover W, CA
35	5	Minarets W, CA
36	5	John Muir W, CA
37	5	Kaiser W, CA
38	5	Kings Canyon NP, CA
39	5	Sequoia NP, CA
40	4	Pinnacles W, CA
41	4	Ventana W, CA
42	5	Dome Land W, CA
43	4	San Rafael W, CA
44	6	San Gabriel W, CA
45	6	Cucamonga W, CA
46	6	San Gorgonio W, CA
47	6	Agua Tibia W, CA
48	6	San Jacinto W, CA
49	6	Joshua Tree W, CA

KEY

<< >> = "Visibility unimportant"
IP = International Park
NP = National Park
NM = National Monument
W = Wilderness Area
##P = Proposed area has been accepted as mandatory

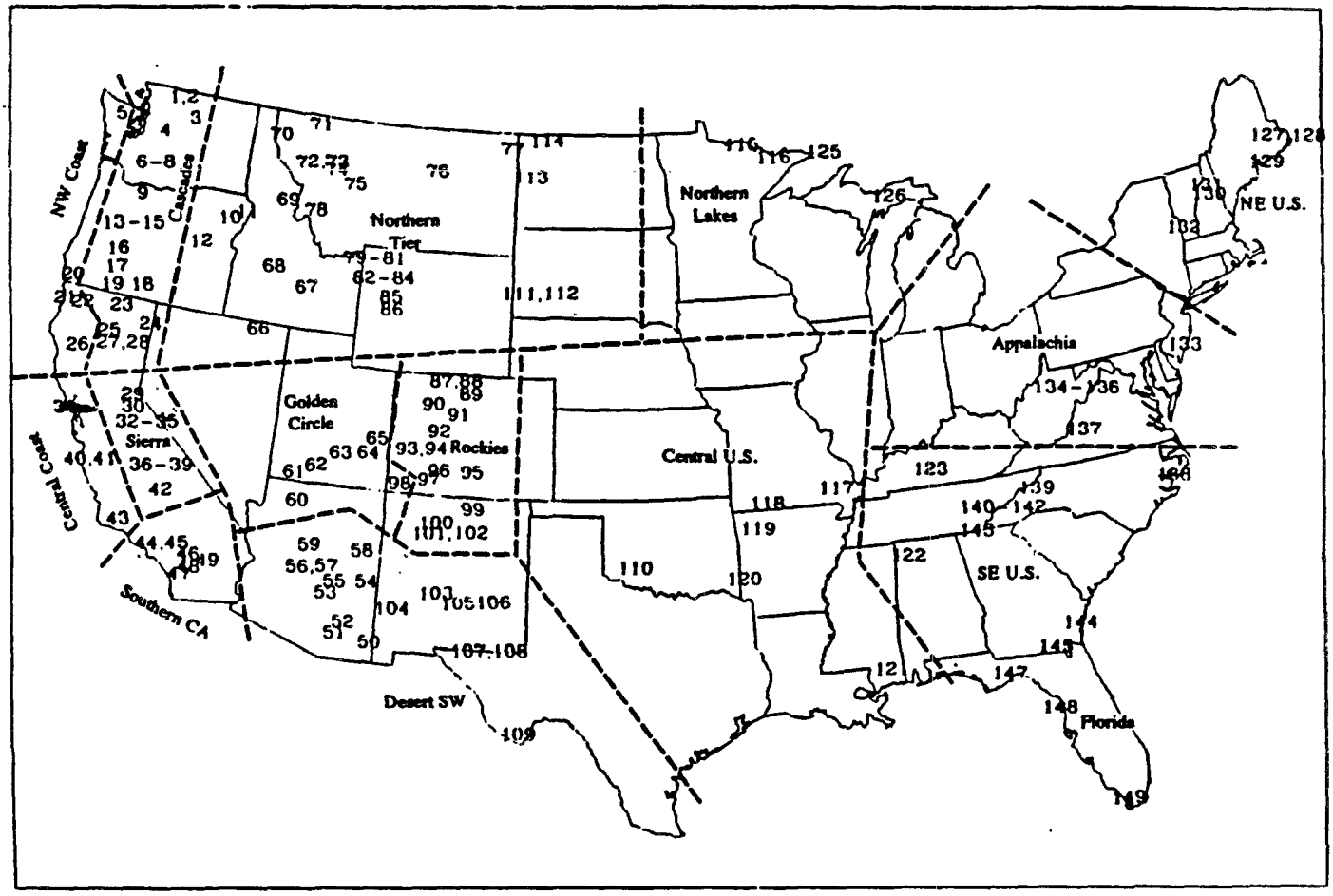
Table 4-2. Continued

11P	7	Chiricahua NM, AZ
50	7	Chiricahua W, AZ
51	7	Saguaro W, AZ
52	7	Galiuro W, AZ
53	7	Superstition W, AZ
54	7	Mount Baldy W, AZ
55	7	Sierra Ancha W, AZ
56	7	Mazatzal W, AZ
57	7	Pine Mountain W, AZ
58	7	Petrified Forest NP, AZ
59	7	Sycamore Canyon W, AZ
60	8	Grand Canyon NP, AZ
61	8	Zion NP, UT
62	8	Bryce Canyon NP, UT
63	8	Capitol Reef NP, UT
64	8	Canyonlands NP, UT
65	8	Arches NP, UT
66	3	Jarbidge W, NV
67	3	Craters of the Moon W, ID
68	3	Sawtooth W, ID
69	3	Selway-Bitterroot W, ID,MT
70	3	Cabinet Mountains W, MT
71	3	Glacier NP, MT
72	3	Mission Mountain W, MT
73	3	Bob Marshall W, MT
74	3	Scapegoat W, MT
75	3	Gates of the Mtn W, MT
76	3	U. L. Bend W, MT
77	3	Medicine lake W, MT
78	3	Anaconda-Pintlar W, MT
79	3	Red Rock Lakes W, MT
80	3	Yellowstone NP, MT,WY,ID
81	3	North Absaroka W, WY
82	3	Washakie W, WY
83	3	Teton W, WY
84	3	Grand Teton NP, WY
85	3	Fitzpatrick W, WY
86	3	Bridger W, WY
87	9	Mount Zirkel W, CO
88	9	Rawah W, CO
89	9	Rocky Moutain NP, CO
90	9	Flat Tops W, CO
91	9	Eagles Nest W, CO
92	9	Maroon Bells-Snowmass W, CO
93	9	West Elk W, CO
94	9	Black Canyon of the Gunnison W, CO
95	9	Great Sand Dunes W, CO
96	9	La Garita W, CO
97	9	Weminuche W, CO
98	8	Mesa Verde NP, CO
99	9	Wheeler Peak W, NM
100	9	San Pedro Parks W, NM
101	9	Bandelier W, NM
102	9	Pecos W, NM
103	7	Bosque del Apache W, NM

Table 4-2. Continued

104	7	Gila W, NM
105	7	White Mountain W, NM
106	7	Salt Creek W, NM
107	7	Carlsbad Caverns NP, NM
108	7	Guadalupe Mountains NP, TX
109	7	Big Bend NP, TX
110	10	Wichita Mountains W, OK
111	3	Badlands W, SD
112	3	Wind Cave NP, SD
113	3	Theodore Roosevelt NMP, ND
114	3	Lostwood W, ND
115	11	Voyageurs NP, MN
116	11	Boundary Waters Canoe Area W, MN
117	10	Mingo W, MO
118	10	Hercules-Glades W, MO
119	10	Upper Buffalo W, AR
120	10	Caney Creek W, AR
121	10	Breton W, LA
122	13	Sipsey W, AL
123	13	Mammoth Cave NP, KY
124	11	<< Rainbow Lake W, WI >>
125	11	Isle Royale NP, MI
126	11	Seney W, MI
127	14	Roosevelt Campobello IP, NB, Canada
128	14	Moosehorn W, ME
129	14	Acadia NP, ME
130	14	Great Gulf W, NH
131	14	Presidential Range-Dry River W, NH
132	14	Lyle Brook W, VT
133	15	Brigantine W, NJ
134	15	Dolly Sods W, WV
135	15	Otter Creek W, WV
136	15	Shenandoah NP, VA
137	15	James River Face W, VA
138	13	Swanquarter W, NC
139	13	Linville Gorge W, NC
140	13	Shining Rock W, NC
141	13	Great Smoky Mountains NP, NC,TN
142	13	Joyce Kilmer-Slickrock W, NC,TN
143	13	Cohotta W, GA
144	12	Wolf Island W, GA
145	12	Okefenokee W, GA
146	12	<< Bradwell Bay W, FL >>
147	12	St. Marks W, FL
148	12	Chassahowitzka W, FL
149	12	Everglades NP, FL
150	13	Cape Romain W, SC
151	3	<< Northern Cheyenne IR, MT >>
152		Bering Sea W, AK
153		Mount McKinley NP, AK
154		Tuxedni W, AK
155		Simeonof W, AK
156		Haleakala NP, HI
157		Hawaii Volcanoes, HI
158		Virgin Islands NP

Figure 4-1. Location of Tabulated Class I Areas and Regions used in the Preliminary Visibility Analysis



relative contribution of each source category to each of the four major anthropogenic aerosol constituents.

Estimates of the 1990 Clean Air Act Amendments-mandated reductions in annual emissions of precursor species from industrial, vehicular, and commercial sources were applied to the 1985 NAPAP inventory at the county level, then aggregated to the state level. Changes in statewide SO_2 and NO_x emissions from electric utilities were taken from projects developed for the EPA by ICF, incorporated assuming high economic growth and national trading of sulfur emissions. This resulted in some states having estimated future SO_2 and NO_x emissions from utilities increasing over the estimate period due to economic growth factors. These increases are over and above any reductions indicated for acid rain control. This situation was addressed later, in more detailed estimates.

Source attribution tables were reconstructed for the Clean Air Act Amendment control scenario; the current (1985) relative contribution of each source category to the four fine particle constituents were scaled by the percent change of annual emission rates in the future case estimate. Extinction budget tables were produced that combined the current estimated anthropogenic concentrations of sulfate, nitrate, organic carbon and elemental carbon with the future emissions case scaling factors. Natural background concentrations of these species (held constant at 1985 estimate levels) were added to these concentrations, and each sum was multiplied be each species' corresponding extinction efficiency to obtain new estimates of extinction. Table 4-3 lists the qualitative current and magnitude of change visibility conditions based on this process.

From this preliminary analysis, the EPA decided to focus resources on more detailed modeling of visibility changes in the East and the Southwest. For the eastern U.S. analysis, the EPA used the available Regional Acidic Deposition Model (RADM) developed under the NAPAP with an additional processor to examine visibility changes due to changes in sulfate concentrations. For the southwestern U.S. analysis the EPA conducted a new modeling analysis. The remaining areas of the country, notably the Pacific Northwest and region just west of the Mississippi River are not likely to see perceptible changes in regional visibility due to Clean Air Act Amendment programs.

Table 4-3. Summary of Preliminary Visibility Analysis Results

No.	Geographical Group	Current Extinction	Estimated Change in Extinction
1	Cascades	Moderate	Small
2	Northwest Coast	Small	Small
3	Northern Tier	Moderate	Small
4	Central Coast	Moderate	Moderate
5	Sierra	Moderate	Small
6	Southern California	Large	Large
7	Desert Southwest	Moderate	Small
8	Golden Circle	Small	Small
9	Rockies	Small	Small
10	Central U.S.	Large	Moderate
11	Northern Lakes	Moderate	Small
12	Florida	Large	Moderate
13	Southeast U.S.	Large	Large
14	Northeast U.S.	Large	Moderate
15	Appalachia	Large	Large

References for Chapter 4

1. Trijonis, J., "Existing and natural background levels of visibility and fine particles in the rural east," Atmos Environ., 16, 2431 (1982).

2. Trijonis, J., R. Charlson, R. Husar, W. Malm, M. Pitchford, and W. White, "Visibility: Existing and historical conditions -- causes and effects," in NAPAP State of Science/Technology Report, National Acid Precipitation Program, Washington, D.C., 1990.

3. Stoeckenius, T.E., H.A. Gray, and C.A. Emery, Report of Results for Work Assignment 2-7, Contract No. 68D00091: Classification of CAAA Implementation on Parks and Wildernesses, letter report to B. Polkowsky, dated February 19, 1992.

4. Gray, H.A., T.E. Stoeckenius, R.E. Morris, L.R. Chinkin, B. Garelick, D.S. Eisinger, L.A. Gardner, and L.W. Richards, Workplan for the Assessment of the Effects of the 1990 Clean Air Act Amendments on Visibility in class I Areas, SYSAPP-91/-124, prepared for the EPA by Systems Applications International, San Rafael, California, 1991.

Chapter 5. Assessment of the Eastern U.S.

The National Acid Precipitation Assessment Program

As part of its comprehensive work, the National Acid Precipitation Assessment Program (NAPAP) estimated changes in visibility for the eastern U.S. that would result from various sulfur emission reduction scenarios. The NAPAP State of the Science Report #24, cites the major cause of man-made visibility impairment for the eastern U.S. as fine particle scattering, accounting for 75 to 95 percent. Of that fine particle scattering, sulfates and organic fine particles account for three-fourths of the dry fine particle mass with sulfuric acid and its ammonium salts accounting for at least half of the fine mass. For the eastern U.S., natural background levels of visibility are considered to be 150 +-45 km of standard visual range on an annual average.[1] This corresponds to an average deciview range of 7.0 to 13.1 dv.

As part of the assessment of changes in effects related to changes in pollutants associated with acid deposition, the NAPAP reviewed the visibility conditions' sensitivity to change for certain reductions in ambient sulfate concentrations. Then NAPAP reviewed several specific emission reduction strategies based on policy options. These visibility changes were presented in the 1990 Integrated Assessment Report. In Chapter 4 of the NAPAP Integrated Assessment, the visibility changes resulting in set levels of reductions and additions (20% increase, 40%, 60%, 80%, 100% decrease) of sulfate were estimated for three locations in the eastern U.S. No changes were made in levels of organic or other fine particle constituents. The integrated assessment found:

- On an annual average basis, calculations show that sulfate contributes 57 percent of light extinction in the rural East.
- That reductions in ambient sulfate concentrations of 20 percent, 40 percent, 60 percent, 80 percent, or 100 percent yield approximately 11 percent, 23 percent, 34 percent, 46 percent, or 57 percent decreases in light extinction.

Chapter 5 of the NAPAP Integrated Assessment focused on several emission reductions scenarios that were being considered for legislation in 1989. The major differences among these scenarios were timing of sulfur emissions reductions. For the purposes of assessing changes in visibility resulting from these emission

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[1] State of Science and Technology Reports, U.S. National Acid Precipitation Assessment Program, Volume III, Report 24, Visibility: Existing and Historical Conditions, Causes and Effects, December 1990.

scenarios, only a 36 percent sulfur dioxide emissions reduction was considered. For that reduction in sulfur dioxide emissions, holding other pollutant fine particle concentrations steady, the Regional Acid Deposition Model outputs were used to calculate sulfate and corresponding visibility changes. A 36 percent reduction in sulfur dioxide emissions, resulting from application of a 1.2 lb of SO_2 per million Btu of heat input emission limitation on all major sources in the Eastern U.S. results in an annual average decrease in light extinction of 21 percent. This improvement in visibility is a slightly greater 26 percent in summer and slightly less in winter.

The geographic pattern of the visibility improvement was investigated by using information from the RADM output on the geographical pattern of sulfate concentration reductions. This was combined with the approximate spatial distribution of baseline light extinction as provided by an analysis of airport data from the State of the Science Report. According to this analysis, the greater visibility improvements are expected to occur in a wide band along the Appalachian mountains from northern Georgia to southern New England, with greater than average improvements also occurring throughout the Ohio River Valley. Figure 5-1, taken from the Integrated Assessment, displays that pattern.

This NAPAP emission scenario is very close to the legislative requirements ultimately adopted in the 1990 Clean Air Act Amendments. The effects on visibility of trading SO_2 emissions across the region for implementation cost reduction purposes as allowed under the Amendments program was not estimated in the NAPAP report.

Reanalysis Using the RADM Engineering Model

Since the NAPAP report, improvements in the RADM results for air concentrations of sulfur and development of emissions databases for regulatory impact assessments have taken place. (See References 3,4,5) In addition, the EPA has developed a visibility post-processor to the RADM air concentration outputs which enables direct calculation of extinction changes, due to changes in fine particle sulfur concentrations. With these changes, a more refined estimate of changes in visibility for the eastern U.S. was possible without extensive new runs of the RADM model which would have been beyond the scope of this report.

Emissions Inventory Revisions

The emissions projections for the revised RADM engineering model runs used in this report were provided by Pechan for the year 2010. Figures 5-2 and 5-3 show the estimated emissions for the 1985 base year and 2010 case for sulfur dioxide and nitrogen

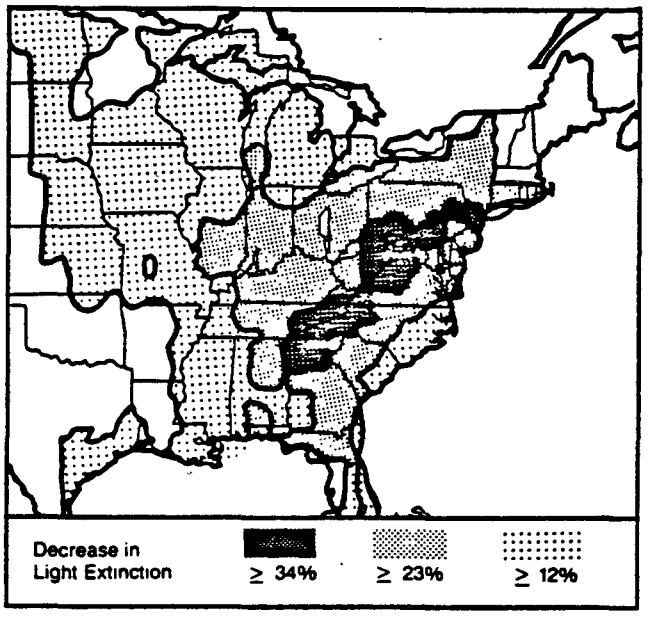


Figure 5-1. Geographical Distribution of Light Extinction from the 1985 Baseline to NAPAP S4 2010 Emissions Estimate.
(Source: NAPAP SOS/T Report #24, 1990)

Figure 5-2. Projected SO2 Emissions for 1990 CAAA, Eastern U.S.
(Source: EPA Compilation of Acid Rain Emissions Inventory work by Pechan, 1991)

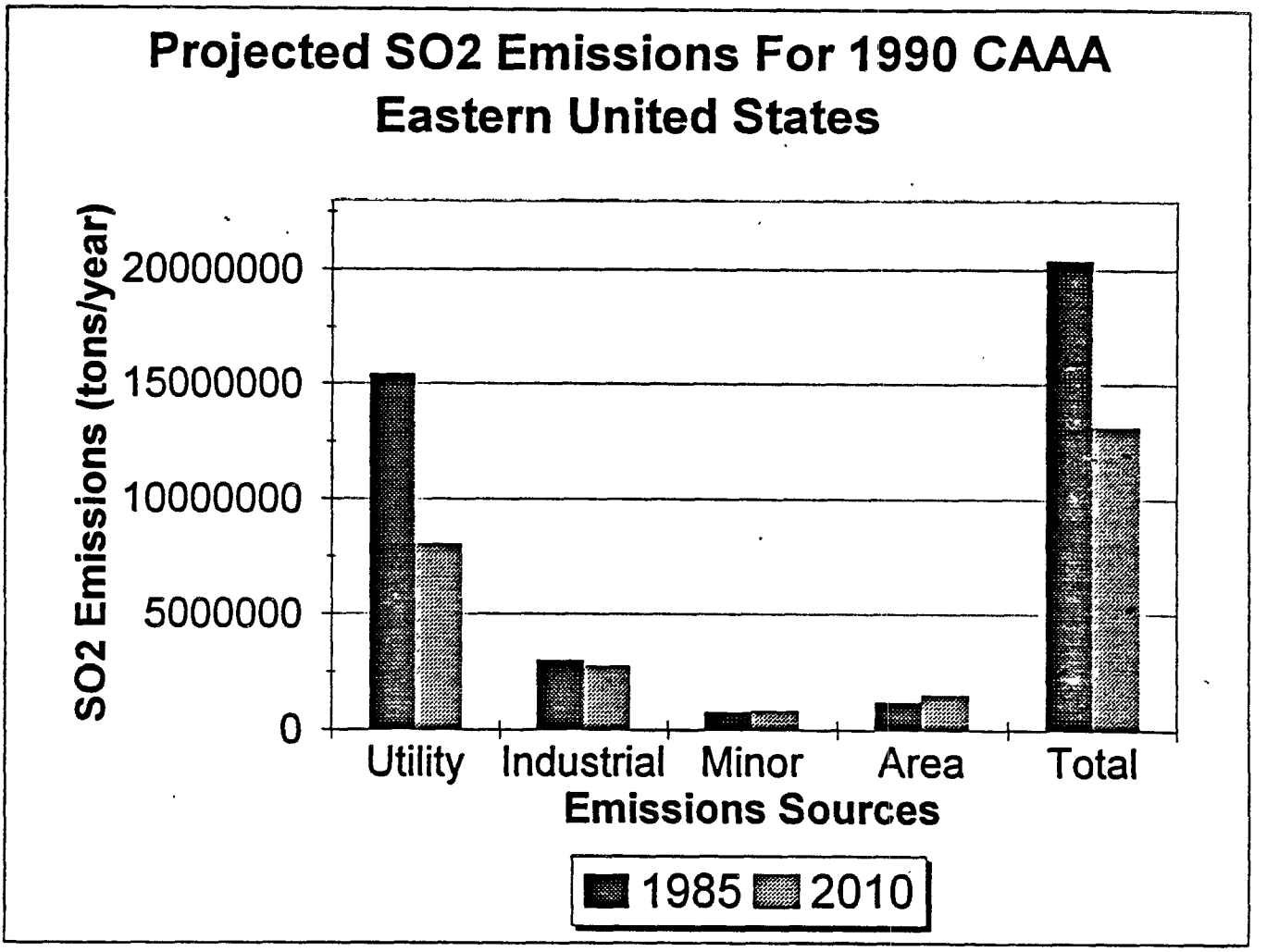
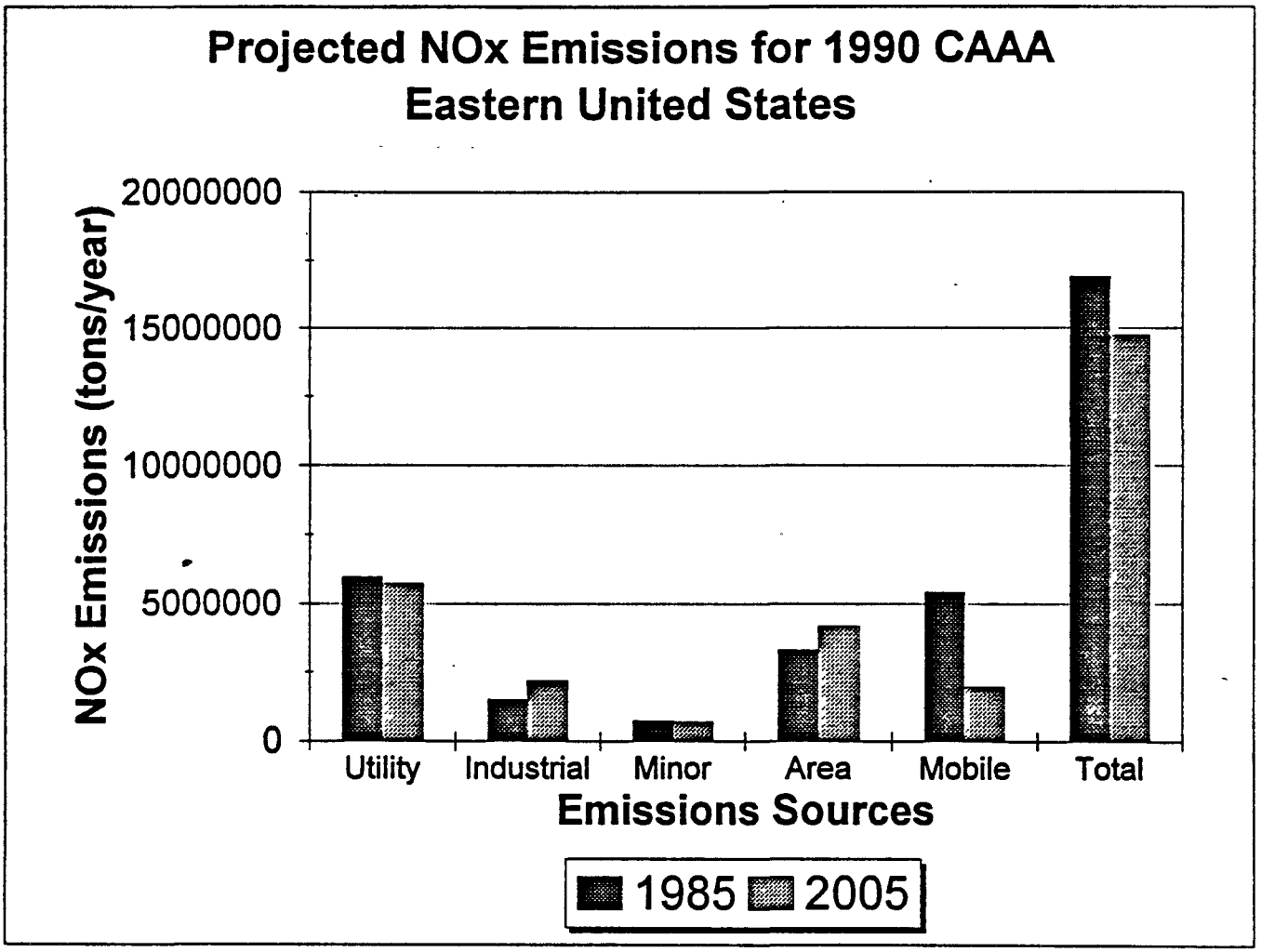


Figure 5-3. Projected NOx Emissions for 1990 CAAA, Eastern U.S.
(Source: EPA Compilation of Acid Rain Emissions Inventory work by Pechan, 1991)



dioxide. Estimates of the changes in reactive hydrocarbon emissions are given in Table 5-1.

Table 5-1. Projected Reactive Hydrocarbon Emissions for 1990 CAAA, Eastern U.S.

Source Group	Projected 1985 Emissions (Million tons)	Projected 2010 Emissions (Million tons)
Major/Industrial Sources	1.63	2.36
Area/Non Traditional Stationary Sources (e.g., dry cleaning)	9.49	8.85
Mobile Sources	3.81	1.08
Total	14.93	12.29

(Source: EPA Compilation of ROM emissions inventory data base on Pechan, 1992)

2010 was the year selected to represent full implementation of Title IV of the 1990 CAAA for many analyses the EPA is conducting. The emissions projections assume no trading of SO_2 allocations. In addition, the emissions reductions for SO_2 for the Canadian program, as predicted by Environment Canada for the 1990 NAPAP Integrated Assessment are included in these projections.

Air Quality Model and Visibility Assessment

In this assessment, a RADM Engineering Model post-processor, (EM-VIS) has been created to calculate hourly estimates of visual range and light extinction for sulfate plus Rayleigh extinction. These estimates were adjusted for total extinction based on NAPAP estimates of relative contribution of components to eastern extinction. Distributions of these estimates were developed for all for mid-day averages (10:00 a.m. to 4:00 p.m.) following the NAPAP methodology. The distributions were rank-ordered by RADM cell for the base emissions and for the new 2010 projections, representing implementation of the 1990 Clean Air Act Amendments for acid deposition. Given the changes in emissions, the meteorology producing the 90th percentile (highest visibility impairment) in 1985 (the base year) is not necessarily the same as that producing the 90th percentile for the year 2010 since RADM accounts for chemistry by pollutant loadings.

Absolute and percentage changes were computed for the deciles for each RADM cell relative to the 1985 base case. Since EM-VIS only models changes in sulfate, the modeled changes in those species

contribution were applied to 1985 baseline levels of the total extinction budget. In general, the 1985 baseline sulfate was well duplicated by the RADM model when compared with monitoring data. The major differences occurred due to underprediction of sulfate by RADM in the upper Midwest. In addition, the monitoring data showed higher levels of sulfate than those predicted by RADM for southern Florida and coastal New England. This could be due to maritime climate contributions to the measured sulfate levels that would not be predicted by RADM's handling of major stationary source emissions.

The results of the analysis of RADM sulfate data indicate that regional visibility will improve in class I areas located from New Hampshire to northern Florida. Figure 5-4 shows the estimated annual median visual range and deciview calculated by RADM with adjustments for non-sulfur extinction for the period 1982-1985 which is the baseline period for this analysis. Figure 5-5 shows the estimated levels for 2010.

The annual distribution has a range of highly impaired days to very clean days. For 1985, ten percent of the days in the year are expected to have visibility levels equal to or less than those indicated in Figure 5-6. Ten percent of the days in the year are expected to have visibility levels equal to or greater than those indicated in Figure 5-7. The amount of improvement varies along this distribution as shown by the expected improvements in the ten percent clearest days and the ten percent most impaired days as modeled by RADM, shown in Figures 5-8 and 5-9, respectively.

Most of the high impairment days occur in summer due to the higher atmospheric temperatures and higher daytime humidity levels. The improvement in median visibility level for the warm season (April through September) between 1985 and 2010 is similar to the level of visibility improvement for the most impaired days of annual distribution, as shown in Figure 5-10. This indicates that the annual distribution very impaired days are dominated by events in the warm season. An examination of the change in the cold season (October through March) average reflects a change more like that of the cleaner days in the annual distribution. See Figure 5-11. The cold season has much better visibility for the region as a whole.

Estimating the Effects of Changes in NO_x

Nitrate aerosols contribute between 6 and 12 percent of the total (Rayleigh included) extinction budget in the rural east as an annual average. By comparison, sulfates contribute between 44 and 62 percent of the annual average extinction budget. Given the magnitude of change expected by 2010 in nitrogen dioxide of approximately 10 to 15 percent reduction, it

Figure 5-4. **Estimated Baseline Annual Average Visibility**
Visual Range (km) and Haziness (dv) based on reconstructed extinction from RADM with adjustment for non-sulfate extinction

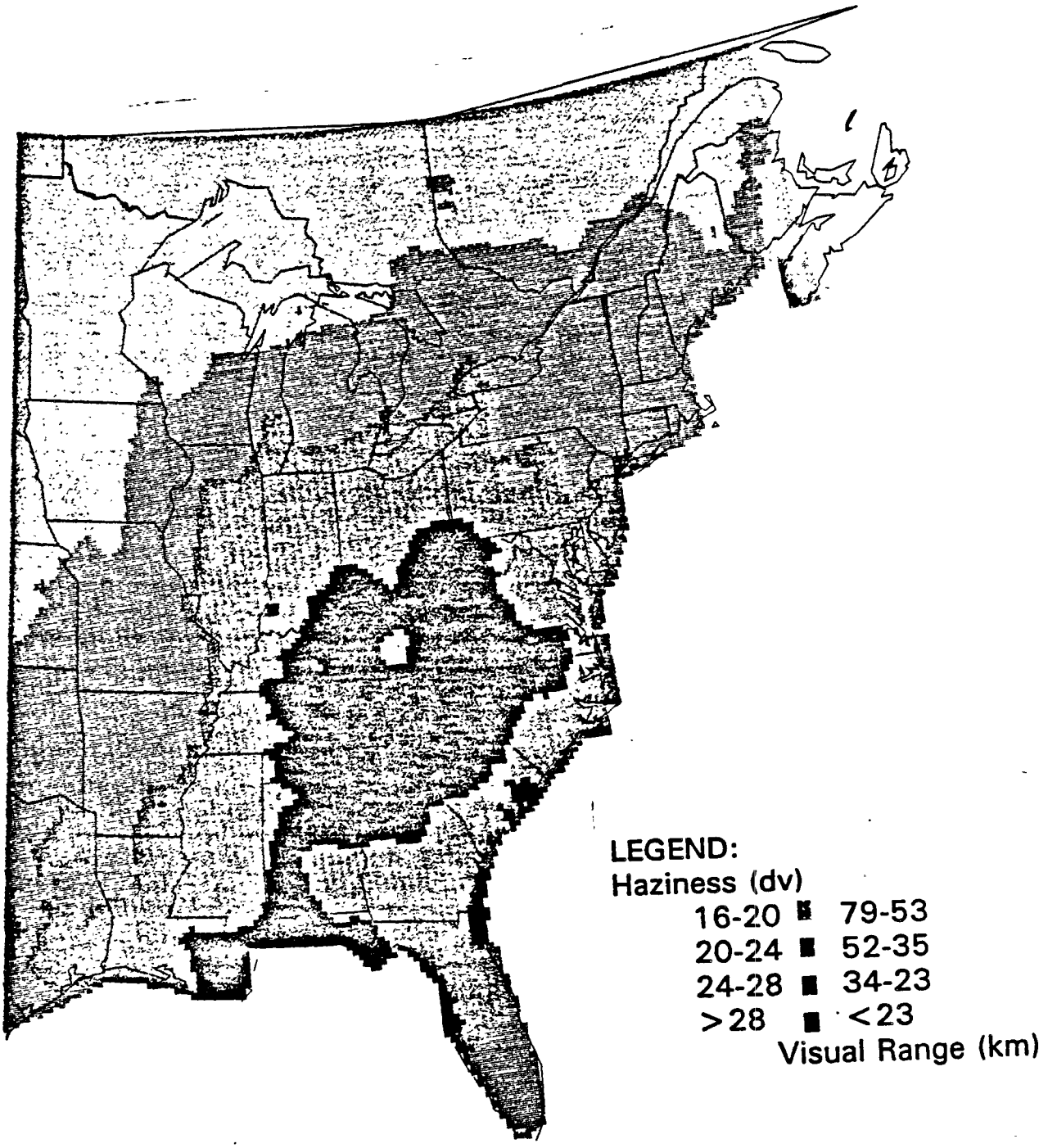


Figure 5-5. **Estimated 2010 Annual Average Visibility**
Visual Range (km) and Haziness (dv) based on reconstructed extinction from RADM with adjustment for non-sulfate extinction

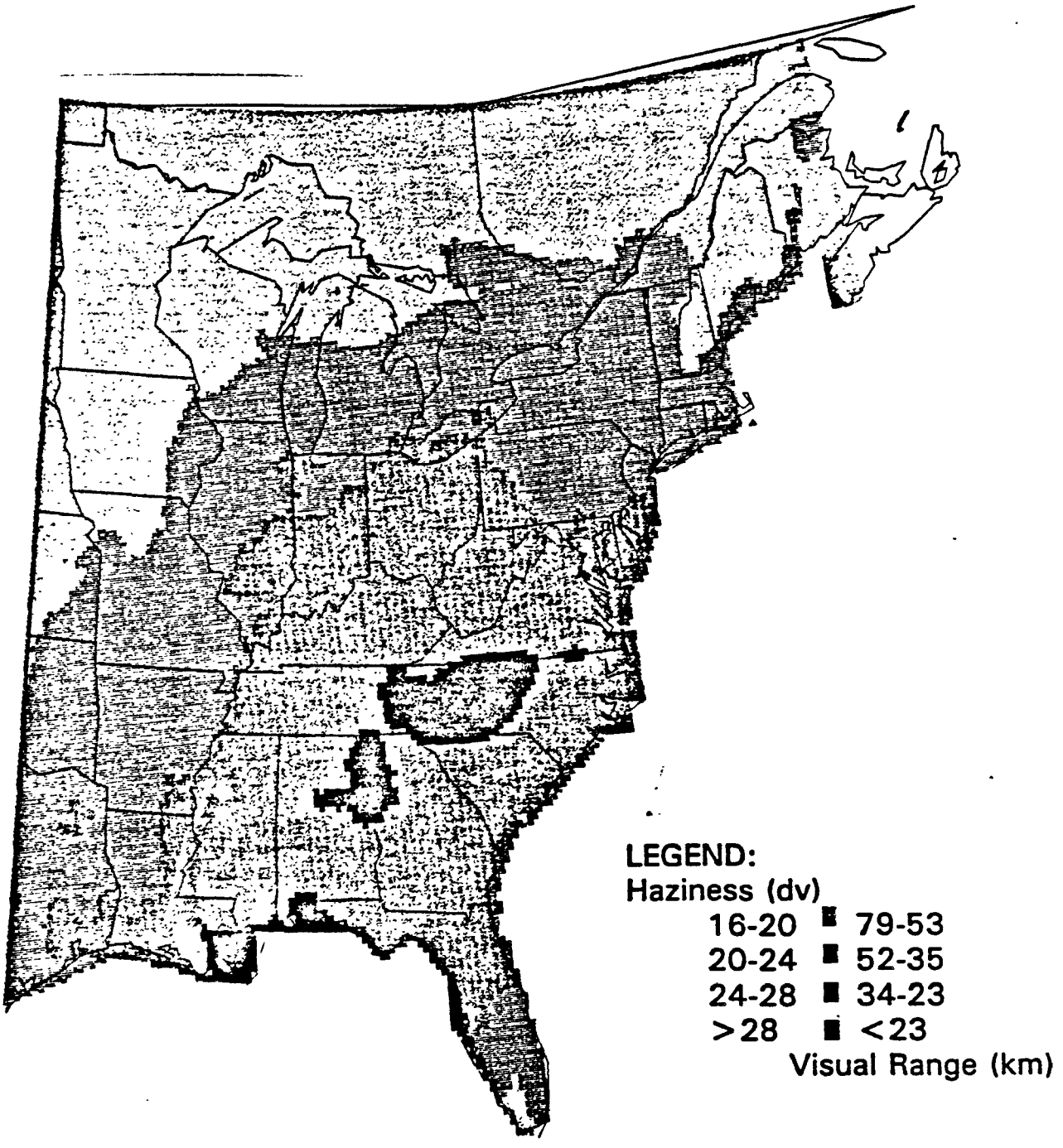


Figure 5-6. Ten Percent of 1985 Days Estimated at Shown Visibility or Worse

Visual Range (km) and Haziness (dv) based on reconstructed extinction from RADM with adjustment for non-sulfate extinction

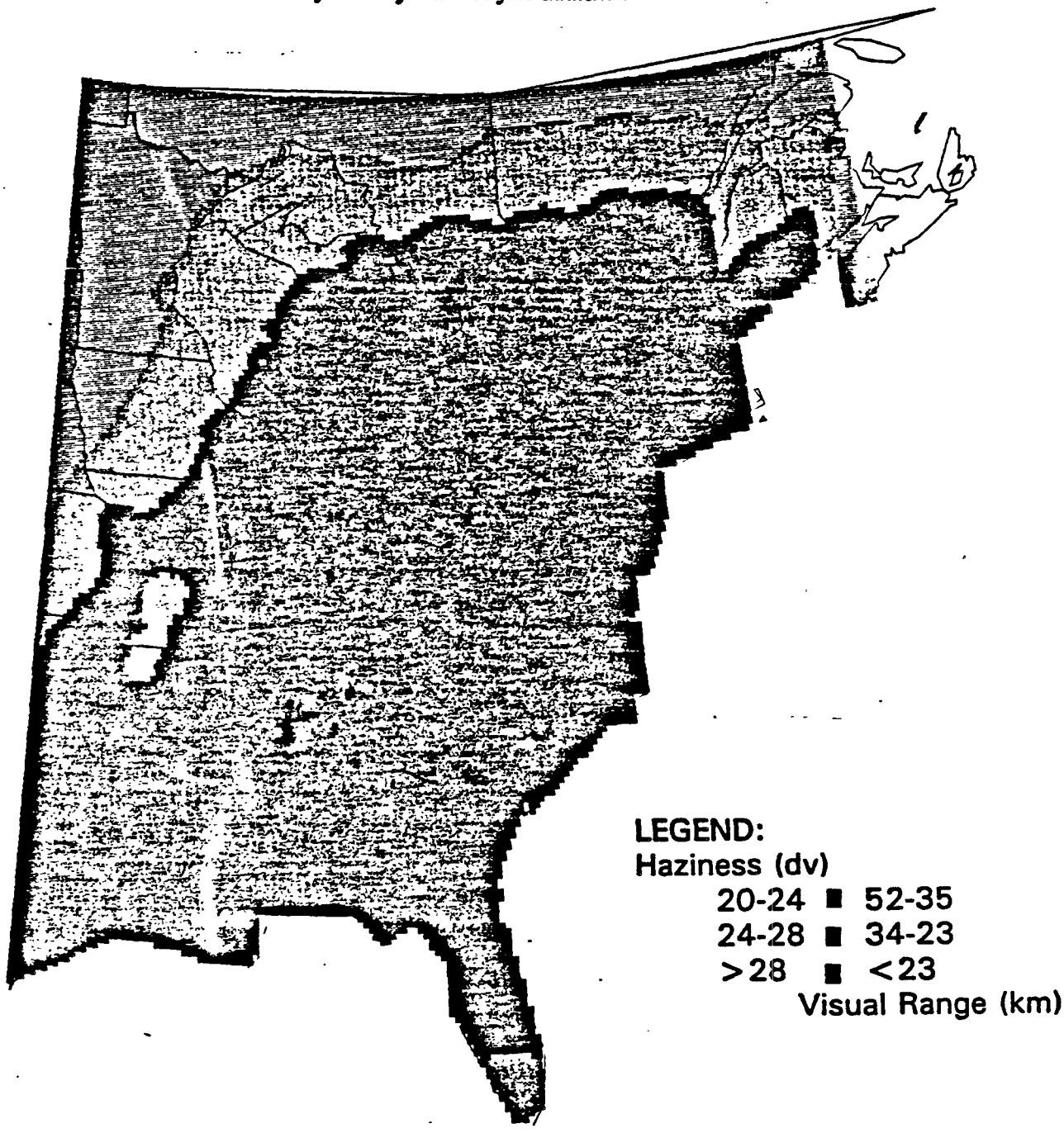


Figure 5-7. **Ten Percent of 1985 Days Estimated at Shown Visibility or Better**

Visual Range (km) and Haziness (dv) based on reconstructed extinction from RADM with adjustment for non-sulfate extinction

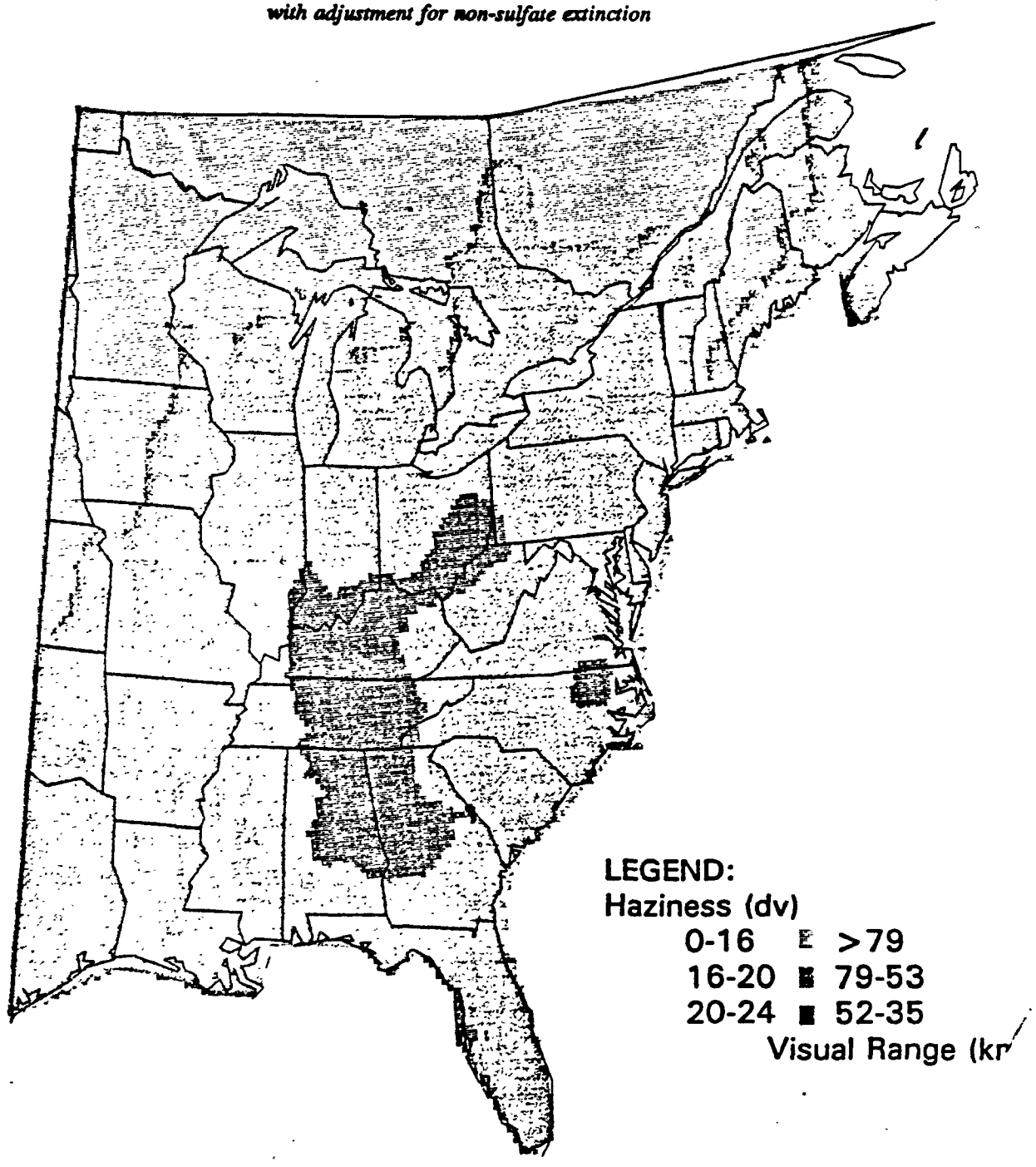


Figure 5-8. Improvement from 1985 to 2010 of the Most Impaired Days

Haziness (dv) based on reconstructed extinction from RADM with adjustment for non-sulfate extinction. A one deciview change is considered perceptible.

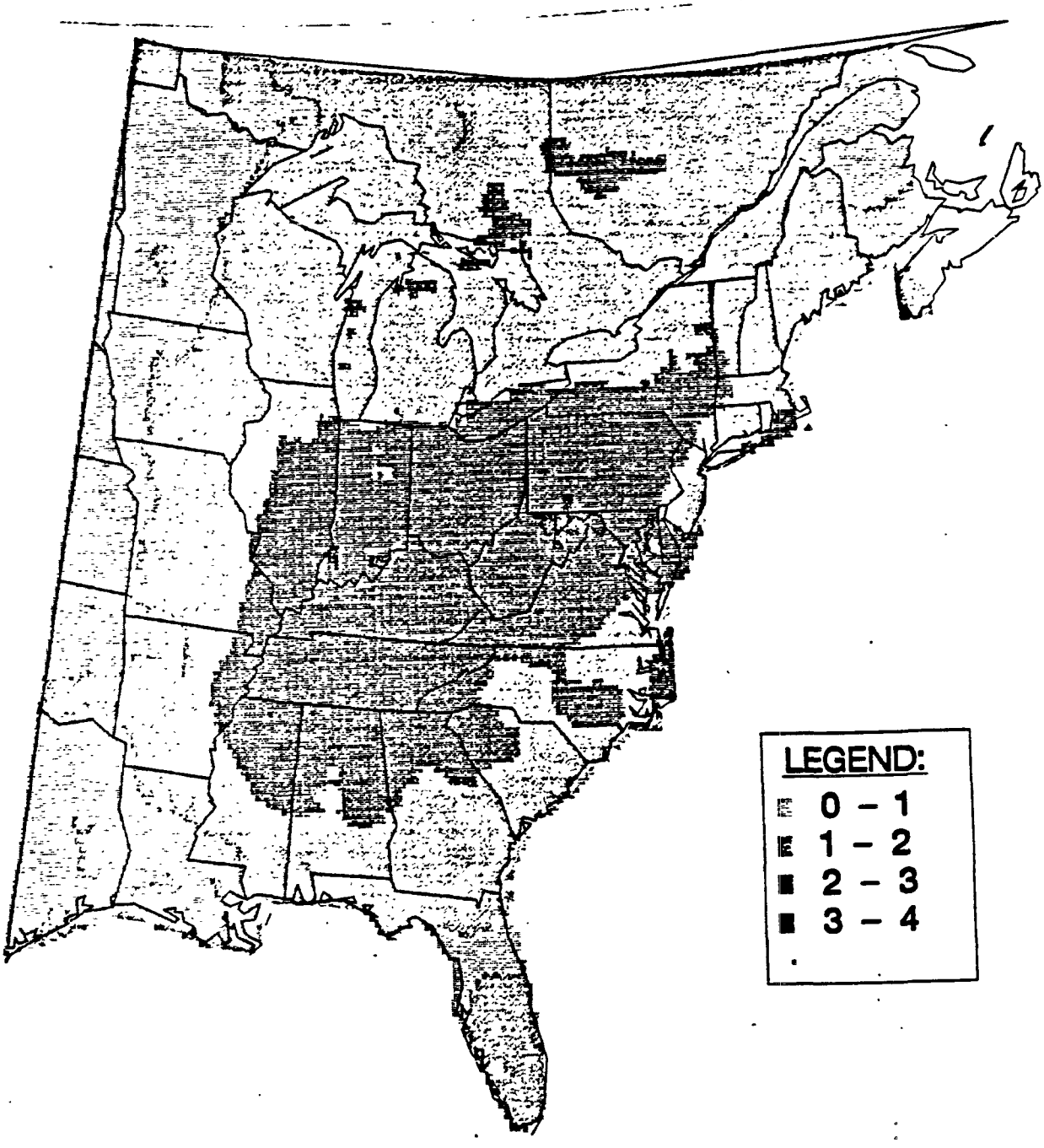


Figure 5-9. Improvement from 1985 to 2010 of the Least Impaired Days

Haziness (dv) based on reconstructed extinction from RADM with adjustment for non-sulfate extinction. A one deciview change is considered perceptible.

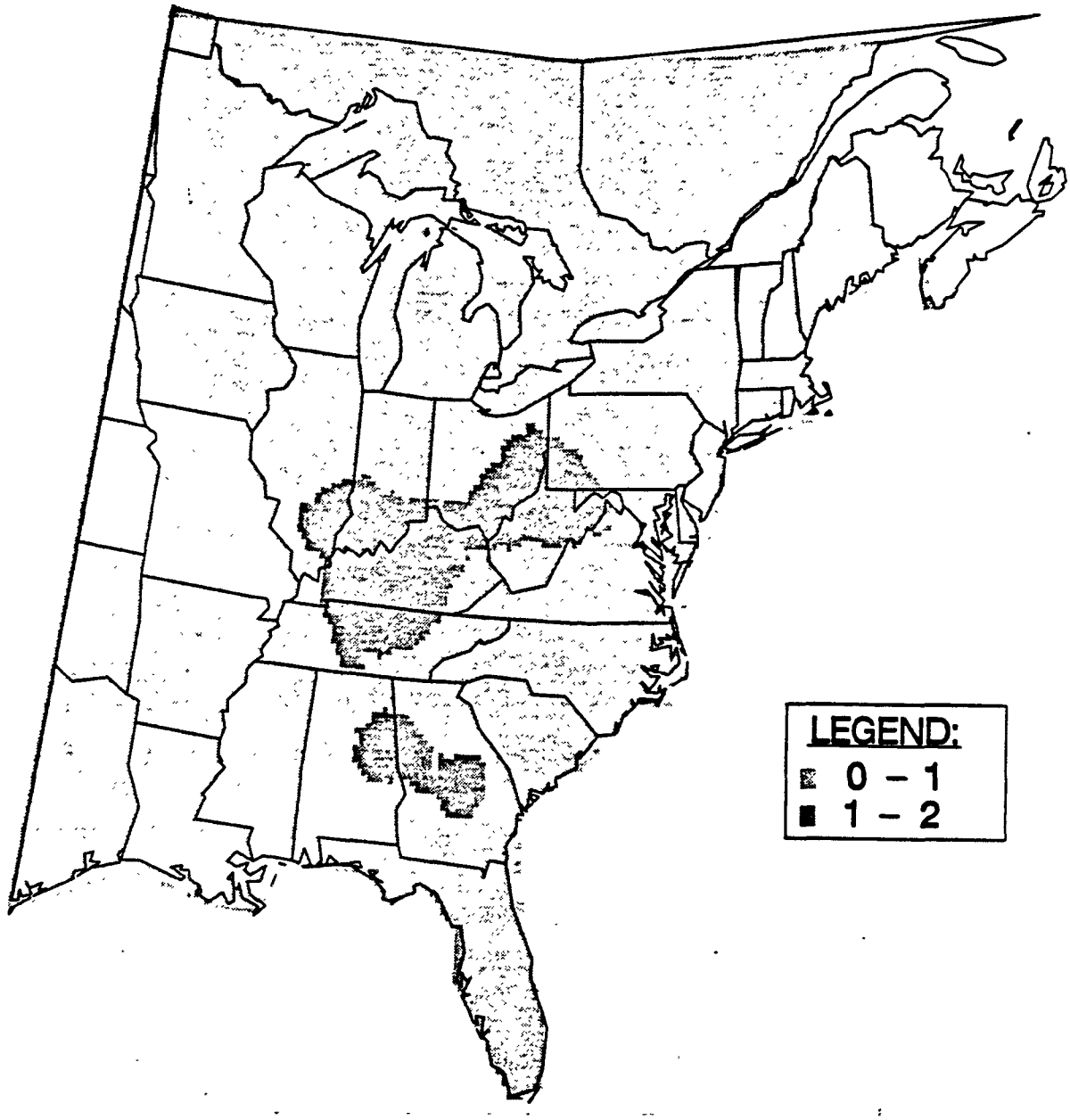


Figure 5-10. Improvement from 1985 to 2010 Average Warm Season (Apr-Sep) Visibility

Haziness (dv) based on reconstructed extinction from RADM with adjustment for non-sulfate extinction. A one deciview change is considered perceptible.

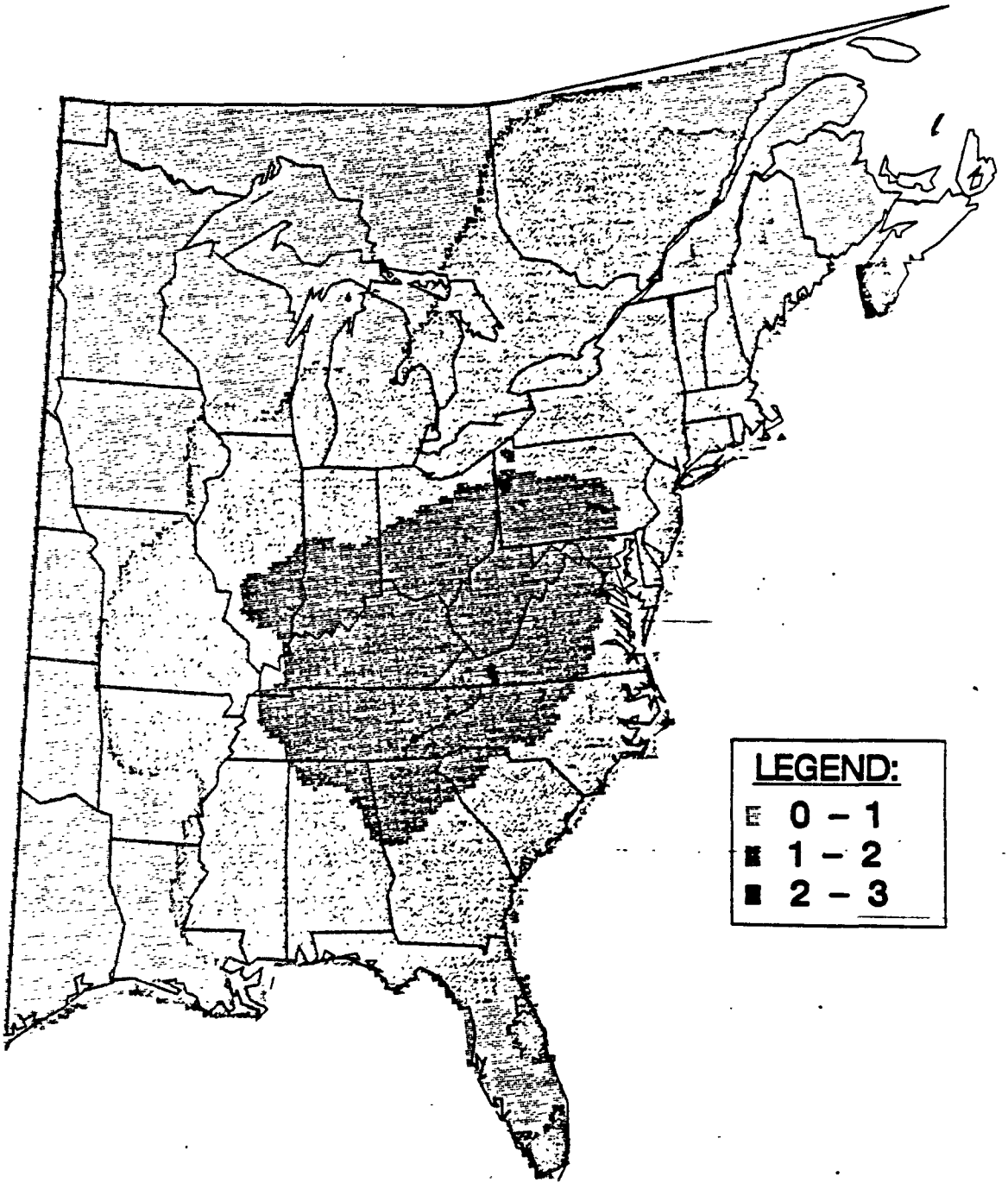
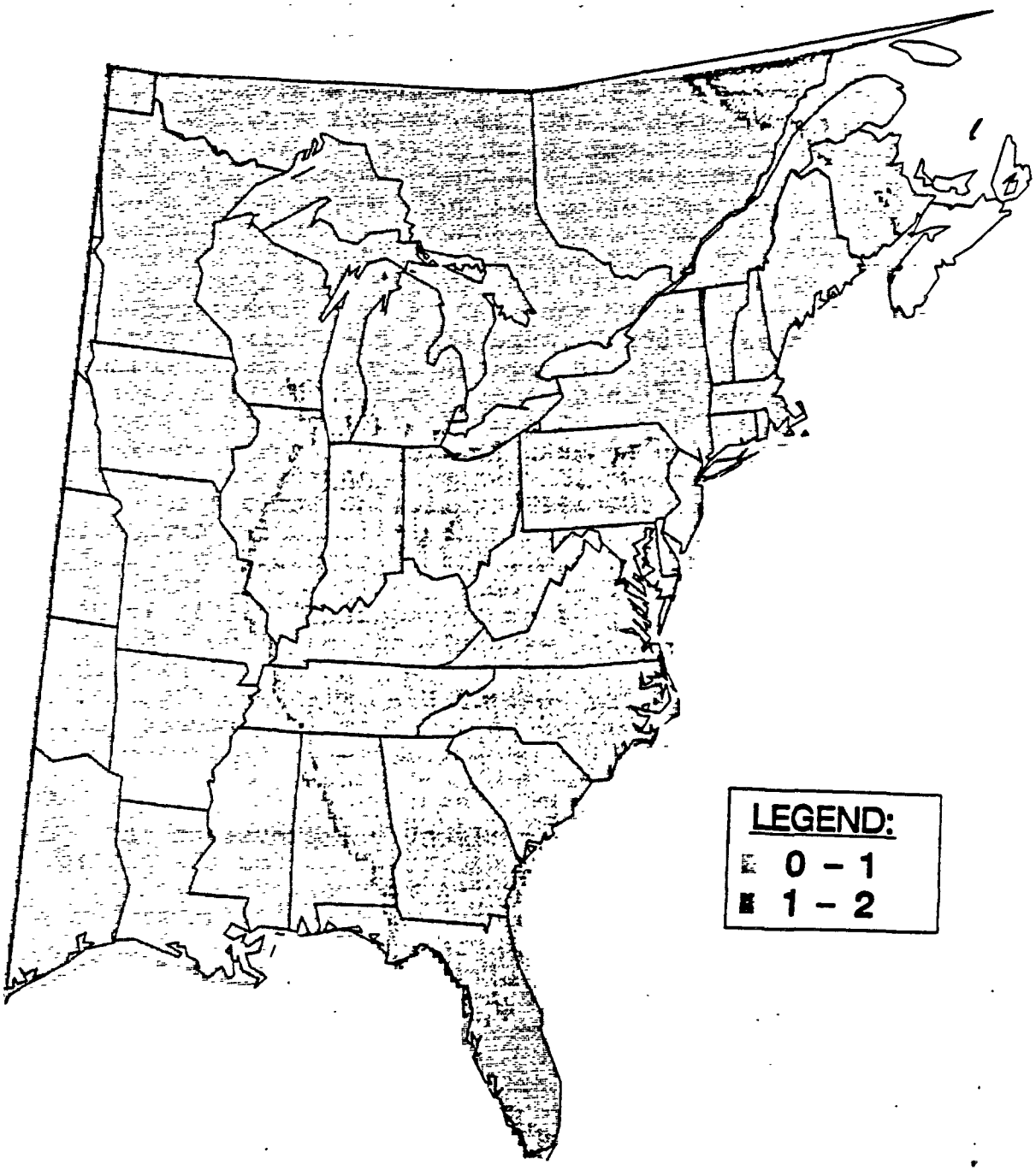


Figure 5-11. Improvement from 1985 to 2010 Average Cold Season (Oct-Mar) Visibility

Haziness (dv) based on reconstructed extinction from RADM with adjustment for non-sulfate extinction. A one deciview change is considered perceptible



is unlikely that rural regional visibility levels will change perceptibly due changes in nitrate levels.

Estimating the Effects of Changes in VOC

There is little information available to distinguish between the man-made organic aerosols which impair visibility from those that occur naturally from vegetation and other causes. The currently monitored levels of organic aerosol are also subject to more uncertainty than those of sulfate and even nitrate. In general, organic aerosols are estimated to be between 15 and 20 percent of the regional fine particle loadings based on IMPROVE monitoring. Since RADM cannot account for the organic compounds, a simple rollback estimation based on estimates of emissions changes is the only means to determine the possible effects of these changes on visibility. From Table 5-1, the eastern region should experience a reduction of man-made VOC of approximately 17.7 percent. Assuming as an upper bound that the entire organic fraction measured by IMPROVE is related to man-made emissions, then a 17.7 percent reduction of that organic fraction would be expected at the class I areas. Reducing the organic aerosol fraction of the extinction budgets developed through the IMPROVE monitoring by 17.7 percent would result in approximately a 3 to 4 percent increase in the total 1985 extinction and a 4 to 5 percent reduction based on the projected 2010 median extinction. This is well below a 1 dv threshold for perceptibility. Highly impaired days that have a larger concentration of organic aerosols would likely see a greater improvement, but it is highly unlikely that all these organic aerosols are man-made. So at these levels of regional reductions of VOC, it is unlikely that the rural class I areas in the eastern U.S. will see regional improvement in visibility related to VOC emissions reductions.

Summary

This assessment indicated that a noticeable improvement in visibility should occur across the eastern U.S. for the entire year, with most of the change occurring in the warm seasons. Winter improvements outside of the central Appalachian area may not be noticeable, depending on the scene. With respect to class I areas, those in the East, particularly along the Appalachian chain should see substantial improvements in regional visibility, particularly in the summer. Class I area improvements were obtained by selecting the RADM grid cell that covered geographic location of each class I area. Table 5-2 lists the changes in visual range and deciview for selected class I areas in the East. Improvement beyond those estimated here would have to come from further reductions in sulfur dioxide emissions coupled with

Table 5-2. Summary of Visibility Changes for Selected Class I Areas (Based on RADM Reconstructed Sulfate plus Non-Sulfate Correction Factor)

Location	Annual Average Visibility km (dv)		10 Percent of Annual Days Have Visibility Less than: km (dv level greater than)		10 Percent of Annual Days Have Visibility Greater than: km (dv level less than)		Warm Season (Apr-Sep) Average Visibility km (dv)		Cold Season (Oct-Mar) Average Visibility km (dv)	
	1985	2010	1985	2010	1985	2010	1985	2010	1985	2010
Acadia NP	50 (21)	53 (20)	17 (31)	21 (29)	76 (16)	78 (16)	50 (21)	54 (20)	55 (20)	59 (19)
Everglades NP	58 (19)	63 (18)	32 (25)	37 (24)	73 (17)	78 (16)	63 (18)	69 (17)	58 (19)	63 (18)
Great Smoky Mtns NP	30 (26)	39 (23)	15 (32)	20 (30)	52 (20)	56 (19)	22 (29)	28 (26)	51 (20)	57 (19)
Lye Brook W	45 (22)	50 (21)	14 (33)	17 (31)	79 (16)	83 (16)	39 (23)	44 (22)	59 (19)	63 (18)
Mingo NWR	41 (23)	44 (22)	16 (32)	20 (30)	62 (18)	66 (18)	36 (24)	42 (22)	59 (19)	62 (18)
Okefenokee NWR	28 (26)	31 (25)	12 (34)	14 (33)	56 (19)	62 (18)	23 (28)	28 (26)	43 (22)	49 (21)
Presidential W	51 (20)	55 (19)	22 (29)	27 (27)	83 (16)	85 (15)	49 (21)	54 (20)	65 (18)	67 (18)
Shenandoah NP	40 (23)	52 (20)	15 (33)	21 (29)	60 (19)	67 (18)	25 (28)	31 (25)	54 (20)	61 (19)
Sipsey W	31 (25)	34 (24)	13 (34)	17 (31)	66 (18)	70 (17)	28 (27)	31 (25)	49 (21)	54 (20)
Voyager NP	69 (17)	72 (17)	43 (22)	46 (21)	86 (15)	88 (15)	83 (16)	86 (15)	61 (19)	67 (18)

NP=National Park, NWR=National Wildlife Refuge, W= Wilderness

reduction in the man-made fraction of organic aerosols, likely to be emissions located outside of urban ozone NAAQS nonattainment areas.

Comparison with Other Studies

The results of this analysis compares reasonably with recent work done by Zannetti et. al, which indicates that sulfur emissions reductions of approximately 12 million tons per year would result in an average improvement in median visual range of 8 percent to

11 percent. This work used a completely different technical approach which separated three years of daily meteorological data into classes of regional transport and regional atmospheric conditions. Their work also focused on the effects on visibility in 4 impact regions rather than much smaller individual grid cells. For each grouping of weather classifications and each impact area, an estimate of visibility improvement was made on a daily basis. The visibility estimates of change were also based on modifying national weather service readings at airports. The smaller change in visibility reported in that paper than in the RADM modeling presented in this report may be due to the following factors: 1) the use of airport data which might underestimate the regional visibility thereby reducing the relative effect of fine particle scattering, 2) differences in emissions changes used in computing reduction of sulfate aerosol, and 3) different treatment of fog and precipitation conditions. Overall, both approaches conclude there will be broad geographic areas of improvement in average visibility, which indicate large changes for certain days when sulfur aerosol dominates the extinction.

Previous work for the EPA conducted in 1984, also assessed changes in eastern visibility using a different air quality modeling system (SAI). That work estimated that a 50 percent reduction in SO_2 emissions across 31 eastern states would improve the regional annual average visibility by 22 percent. This work underestimated visibility improvement, because it failed to account for changes in the boundary conditions that would result from emissions controls Therefore, within the realm of uncertainties for air quality modeling and the translation of air quality data to visibility estimates, that estimate is essentially in agreement with work performed for this report.

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9. Zannetti, P., Tombach, I., Cvencek, S., and Balson, W. "Calculation of Visual Range Improvements from SO_2 Emission Controls -- II. An Application to the Eastern United States" *Atmospheric Environment*, Vol 27A, No. 9.

10. Visibility and Other Air Quality Benefits of Sulfur Dioxide Emissions Controls in the Eastern United States, Systems Applications, Inc. Prepared for the U.S. Environmental Protection Agency, Draft Final Report, January, 1984.

Chapter 6. Southwestern U.S.

For class I areas in the southwestern U.S., a more comprehensive analysis was carried out to estimate the changes in visual range due to implementation of the CAAA on a finer spacial and temporal scale than in the preliminary analysis. Figure 6-1 shows the geographic domain of the southwestern modeling analysis. This chapter summarizes the steps taken in preparing emissions inventory for the modeling, the modeling approach, and the results.

Emissions Inventory Development

Three annual emission inventories were prepared for the southwestern U.S. modeling domain:

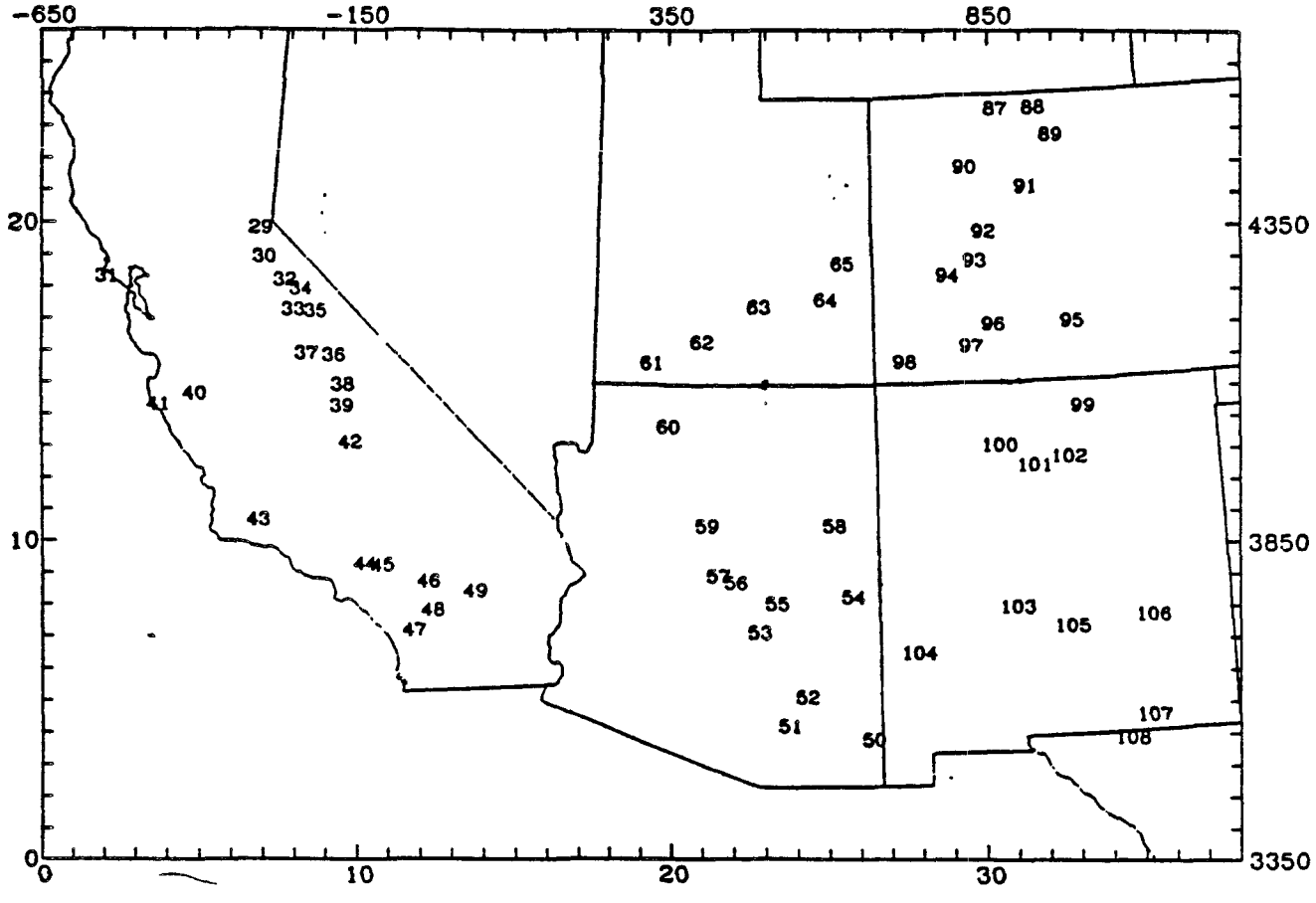
- a 1988 base case inventory,
- a 2005 base case inventory designed to reflect emission levels which would be expected in the absence of the 1990 CAAA, and
- a 2005 control case inventory which reflects anticipated emission reductions resulting from implementation of the 1990 CAAA (excluding provisions of Section 169B).

For purposes of this modeling, all provisions of the amendments were assumed to be fully implemented as of 2005. Thus, control measures designed to bring the Los Angeles area into attainment with the national ambient air quality standard for ozone by 2020 were assumed to be fully implemented by 2005.

Each annual inventory was temporally disaggregated in the manner described below, resulting in one inventory for each month modeled (April, July, October, and December).

Anthropogenic sources of NO_x, SO_x, and PM were included in the inventories -- biogenic sources of these species were not included. For non-mobile source categories, emissions of PM_{10} and $PM_{2.5}$ (particles equal to or smaller than 10 μm and 2.5 μm aerodynamic diameter, respectively) were estimated from total suspended particulate (TSP) emissions by assuming a representative size distribution for each source category. $PM_{2.5}$ emissions were further speciated into primary organic and elemental carbon emissions for each source category. For mobile sources, estimates of PM_{10} emissions were obtained directly from the PART5 model (Shepard, Gray, and Heiken, 1992). Speciation factors were applied to these estimates to estimate the primary organic and elemental carbon fractions.

Figure 6-1. Southwestern Modeling Domain and Location of Class I Areas



Modeling domain for the southwest visibility modeling study; numbers indicate locations of Class I areas.

Data Sources

The 1985 National Acid Precipitation Assessment Program (NAPAP) emission inventory, Version 2 (EPA, 1989) was used as the basis for the annual inventories. This inventory includes emission estimates, stack parameters, seasonal, weekly, and daily operating schedules and location information for all major point sources (defined as sources with annual emissions of any one species of 100 TPY or more), area source emissions by county (area sources include total emissions from individual point sources emitting less than 100 TPY), and mobile source emissions by county. Extensive data quality checking was performed on the NAPAP inventory in connection with a previous modeling study of the southwestern U.S. (Gray et al., 1991b). Missing, inconsistent, or unrealistic source identification, location, operating schedule, and stack parameter data were replaced with best available estimates.

Electric utility emission estimates in the 1985 NAPAP inventory are largely out of date and were not used for this study. Instead, the National Allowance Data Base, Version 2.1 (NADB V2.1; Rothschild, 1992) was used as the basis for the 1988 utility emission estimates together with updated information for specific plants obtained from utility industry sources (Teague, 1992, 1993). Future year (2005 base and control case) utility emissions were obtained from the regulatory impact analyses for the acid rain and NO_x regulations implementing Title IV of the 1990 CAAA (ICF, 1992a,b) as described below.

Few data are available regarding emissions from northern Mexico which may effect visibility in U.S. class I areas. SO_x emission estimates were obtained for two large smelters in the border area (Nacozari and Cananea) using data obtained in a previous study (Gray et al., 1991b). NO_x and PM emissions for these facilities were estimated assuming species emission ratios similar to those at large U.S. smelters. Emissions from other sources in Mexico were not included in the inventory.

U.S. smelter stack parameters were obtained primarily from the 1985 NAPAP inventory, with corrections incorporated as in the previous study mentioned above. Emissions estimates for smelters located in Arizona were obtained from the Arizona Department of Environmental Quality (Costello, 1992). Emissions estimates for the Kennecott Utah copper smelter were obtained from the plant operator (Salmon, 1993) as were estimates for the two New Mexico smelters (Kendall, 1993).

Emission Inventory Processing

Modeling inventories were prepared using the Emission Preprocessing System (EPS 2.0; EPA, 1992a) in accordance with EPA

procedures (EPA, 1991b). County-level area and mobile source emissions in the NAPAP inventory were allocated to grid cells in the modeling domain based on population density and county area. Mobile source NO_x emissions were estimated by applying emission factors obtained from the MOBILE 5.0 model (EPA, 1992b) to the appropriate county vehicle miles traveled (VMT) estimates (obtained as described below) and spatially allocated to each grid cell based on population density. Mobile source PM and SO_x emission factors were estimated using the PART5 model recently developed by Systems Applications International (Shepard, Gray, and Heiken, 1992). The annual inventory was temporally disaggregated using seasonal and diurnal adjustment factors. Point sources were disaggregated on a point-by-point basis using the operating schedule information in the NAPAP inventory together with diurnal profiles provided in the EPS 2.0. Area and mobile sources were disaggregated by source category using EPA default temporal profiles.

Preparation of 1988 Inventory

Non-utility stationary source emission estimates for 1988 were obtained by applying appropriate 1985 - 1988 activity indicator projection factors to the 1985 NAPAP estimates. State-level projection factors for 2-digit SIC (standard industrial code) designations and NAPAP area source category codes were obtained from projected demographic and industrial economic activity indicators developed by the Department of Commerce's Bureau of Economic Analysis. Data for smelters in Arizona and New Mexico, 1988 emission estimates were obtained from other sources as noted above.

Mobile source emissions were estimated by first calculating the 1985 VMT levels from total emissions and associated emission factors listed in the 1985 NAPAP inventory. These VMT estimates were then grown to 1988 levels by applying national average VMT growth factors developed by Argonne National Labs. The national VMT growth factors were prorated to each state based on the change in state population between 1985 and 1988. Finally, the 1988 VMT estimates were combined with emission factors obtained from MOBILE 5.0 and PART5 to compute 1988 mobile source emissions.

Utility SO_x emissions for 1988 were assumed to be approximately equal to the 1985 - 1987 average fuel use times the 1985 emission factor for each source as listed in the NADB V2.1 file (Rothschild, 1992). Although not specific to 1988, emission estimates obtained in this way were judged to be more accurate than those obtained by applying projection factors to the 1985 NAPAP utility emissions. Utility 1988 NO_x and PM emissions were estimated by scaling the 1985 NAPAP NO_x and PM emissions for each source by the ratio of NADB SO_x emissions to 1985 NAPAP SO_x

emissions. For a significant number of the larger power plants, specific 1988 emission estimates for SO_x, NO_x, and PM were obtained from operating companies as compiled by the Utility Air Regulatory Group (Teague, 1992).

Preparation of 2005 Base Case Inventory

Non-utility stationary and mobile source emission estimates for the 2005 base case inventory were obtained by applying 1988 - 2005 projection factors to the 1985 NAPAP inventory in a manner analogous to that used to obtain the 1988 inventory. It should be noted that the use of demographic and economic indicators projected to 2005 results in significantly more uncertain emission estimates than is the case for 1988. Projection factors were not used to estimate future U.S. smelter emissions which were obtained from other sources as described above. Emissions from the Mexico smelters were projected based on the applicable industry projection factors for New Mexico. A summary of smelter SO_x emissions is presented in Table 6-1. Motor vehicle fleet turnover effects are incorporated via the MOBILE 5.0 emission factor model.

Utility NO_x and SO_x emission estimates for 2005 were calculated by ICF Resources using results from the Coal Electric Utility Model (CEUM) for the so-called "EPA Low" base case originally developed in 1989 (ICF, 1989) and subsequently used in the acid rain regulation regulatory impact analysis (ICF, 1992). The low base case assumes electricity sales growth in the states included in the modeling domain ranging from two to three percent per year through 2000 and one to two percent per year thereafter. Although the projected oil and gas prices assumed in this base case are higher than most current projections, distortions in emission estimates generated by this assumption were minimized by updating the EPA forecasts using updated power plant build decision information in the NADB V2.1 file, and recent data from the National Electric Reliability Council (NERC) and the Energy Information Agency (EIA). To account for the much lower gas prices currently projected, all new coal-fired capacity included in the EPA base case that is not confirmed by NADB or NERC/EIA information were assumed to be built as gas-fired units. Furthermore, the 1000 MW Allen coal-fired generating station projected in NADB but not included in the EPA Low base case was assumed to be indefinitely deferred. These changes resulted in the projection of essentially no new coal-fired and very little new oil-fired generating capacity. All new capacity which was included in the calculations for which location information was unavailable was assumed to be distributed over existing sites. Table 6-2 summarizes SO_x emissions from the eight layout utility sources in the modeling domain.

Table 6-1. Smelter SO_x Emissions (10^3 TPY).

		2005	
	1988	Base	CAAA
Arizona			
Magma	113	73	73
Miami-Inspiration	11	12	12
Asarco	25	21	21
New Mexico			
Phelps Dodge	66	38	38
Chino Mines	35	23	23
Utah			
Kennecott Minerals	27	19	1
Mexico			
Nacozari	29	32	32
Cananea	64	70	70

Table 6-2. Eight Largest Power Plants Annual SO_x emissions (10^3 TPY).

		2005	
	1988	Base	CAAA
Navajo	68.4	8.1	8.1
Mohave	41	41	41
Four Corners	33	30	25
San Juan	28	25	25
Comanchee	13	23	16
Cholla	17	22	22
Pawnee	12	18	18
Huntington	11	18	13

SO_x emissions at the Navajo Generating Station power plant in Arizona were adjusted to reflect 90 percent scrubbing as is currently required under provisions of the Clean Air Act independent of the 1990 CAAA. For sources in California, utility NO_x emissions were restricted to the lesser of the CEUM predictions and NO_x emission limits imposed by state and local authorities before 1990. Utility PM emissions were estimated from projected fuel consumption by using uncontrolled PM emission factors from EPA AP-42 and applying a typical control efficiency of 98.5 percent.

Preparation of 2005 CAAA Case Inventory

A 2005 CAAA or "control" case inventory was obtained by adjusting the 2005 base case inventory to account for the effects of emission controls expected to result from implementation of the 1990 CAAA. A summary of the emission control provisions of the 1990 CAAA by title and affected non-attainment areas together with a brief description of the methods used to account for the provisions in the inventory is presented in Table 4-1. Provisions calling for VOC emission reductions were not addressed since VOCs were not included in the inventory. For stationary sources, Title I NO_x controls [e.g., reasonably available control technology, (RACT)] were applied using the control efficiency (CE), rule effectiveness (RE) and rule penetration (RP) factors. These factors conform to those used in the EPA's emission projections for the Northeast Ozone Transport Region (EPA, 1991a). Affected nonattainment areas are identified in Table 6-3. It should be recognized that, as in any inventory development process, the selection of appropriate CE, RE, and RP factors represents a major source of uncertainty.

Title I of the 1990 CAAA call for implementation of certain control measures (RACM, including RACT and BACM, including BACT) for sources of particulates in moderate and serious PM_{10} nonattainment areas respectively. At the time this report was prepared, however, insufficient information was available with which to estimate specific emission reductions which might be expected to result from these control measures. For this study, therefore, a linear rollback technique was used in which PM_{10} emissions in nonattainment areas were assumed to be reduced across the board by an amount proportional to the ratio of the 1990 design value to the 24-hour average national ambient air quality standard of 150 $\mu g/m^3$; the 24-hour standard was assumed to be the controlling standard in all cases. For certain areas which were nearly in attainment as of 1990, PM emissions were assumed not to grow beyond 1988 levels.

Table 6-3. Ozone Nonattainment Areas Within the Modeling Domain, with Minimum Source Size for RACT Applicability.

Ozone Nonattainment Status	Minimum Source Size (tons NO_x/year)	Nonattainment Areas
Marginal	100	Reno, NV
Moderate	100	Salt Lake City, UT Monterey Bay, CA Phoenix, AZ San Francisco Bay Area, CA Santa Barbara, CA
Serious	50	El Paso, TX Sacramento, CA San Joaquin Valley, CA
Severe	25	SE Desert AQMA, CA San Diego, CA‡ Ventura Co., CA
Extreme	10	Los Angeles SCAB, CA‡

‡ Reformulated gasoline areas.

For on-road motor vehicles, emission reductions anticipated as a result of the following provisions of the 1990 CAAA were included in addition to the projected VMT and fleet turnover effects included in the 2005 base case inventory:

- enhanced inspection and maintenance (I/M) programs in serious, severe, and extreme ozone nonattainment areas (areas with design values equal to or higher than 160 ppb and CO nonattainment areas with design values of 12.7ppb and above);
- basic I/M programs in moderate ozone nonattainment areas (areas with design values equal to or higher than 138 ppb but less than 160 ppb and CO moderate nonattainment areas with design values 12.7ppb and below);
- reduced fuel Reid vapor pressure (RVP) specifications;
- new emission standards for light duty gasoline vehicles and trucks;
- reformulated gasoline in the Los Angeles and San Diego nonattainment areas.

Clean fuels provisions were not addressed since only hydrocarbon emission reductions are predicted for these fuels by MOBILE 5.0. Mobile source PM and SO_x emissions were estimated using emission factors from the PART5 model.

Utility SO_x and NO_x emissions for the 2005 CAAA case were estimated using results from CEUM runs based on the "RIA low trading case" as described in the acid rain regulatory impact analysis (RIA) prepared by ICF Resources. These results take into account the Title IV Phase II SO_2 emission allowances, which are for the most part based on an emission rate of 1.2 lb/MMBtu or less. The effects of trading of allowances between sources and allowance banking are accounted for by the CEUM. New units are allocated allowances if construction commenced by the end of 1990 and they are expected to be on-line by the end of 1995. All other new units were assumed to be required to purchase allowances to cover their emissions. As in the 2005 base case, scrubbers with 90 percent SO_2 average removal efficiency were assumed to be installed at the Navajo Generating Station power plant.

Utility NO_x emissions were calculated assuming an emission limit of 0.45 lb/MMBtu for existing tangentially-fired coal units and 0.5 lb/MMBtu for existing wall-fired coal units and for any new coal-fired units, as called for in Title IV. Since rules allowing for averaging of NO_x emissions across units for purposes

of meeting these limits have not been finalized, the effects of such averaging were not considered. In addition to these limits, the 0.2 lb/MMBtu and 0.3 lb/MMBtu NO_x RACT limits for tangential and wall-fired gas and oil units, respectively, were imposed for sources located in ozone nonattainment areas.

Utility PM emissions were calculated as in the 2005 base case inventory, but using the fuel consumption estimates calculated from the CEUM for the "RIA low trading case."

Summary Comparison of Emission Inventories

Figures 6-2 through 6-5 provide a comparative summary of the three annual emission inventories generated for this project (1988, 2005 base case, 2005 CAAA case). Only the fine particle ($PM_{2.5}$) fraction of the PM emissions is shown in these figures. Figure 6-2 shows total emissions by species. The largest reductions in the 2005 CAAA case are for NO_x emissions which drop below 1988 levels. SO_x emissions decrease slightly while fine particle emissions decreases in the CAAA case only partially offset the expected growth from 1988 levels.

Motor vehicle and area sources dominate the NO_x emissions (Figure 6-3), with the bulk of the total reduction expected to come about as a result of mobile source controls.

For the modeling region, total utility SO_x emissions are comparable to those from other point sources (e.g., smelters, refineries, pulp mills) and area sources (Figure 6-4). Only utility sources are expected to contribute to decreased SO_x emissions as a result of the 1990 CAAA.

Fine particle emissions are dominated by motor vehicles and area sources (Figure 6-5). A significant amount of growth in the motor vehicle component is expected due to projected VMT growth and the lack of any specific PM controls for this source category in the 1990 CAAA. This growth accounts for the bulk of the increase in total $PM_{2.5}$ emissions. Area source PM emissions are expected to decrease due to the requirement to bring certain areas into attainment with the PM_{10} NAAQS.

Seasonal variations in NO_x and SO_x emissions were estimated to be generally small, while the seasonal variations in $PM_{2.5}$ emissions exceed the expected increase from 1988 to the 2005 base case.

Figure 6-2. Estimated Total Gridded Annual Emissions for the Southwestern Analysis (1988, 2005 Base, 2005 Control)

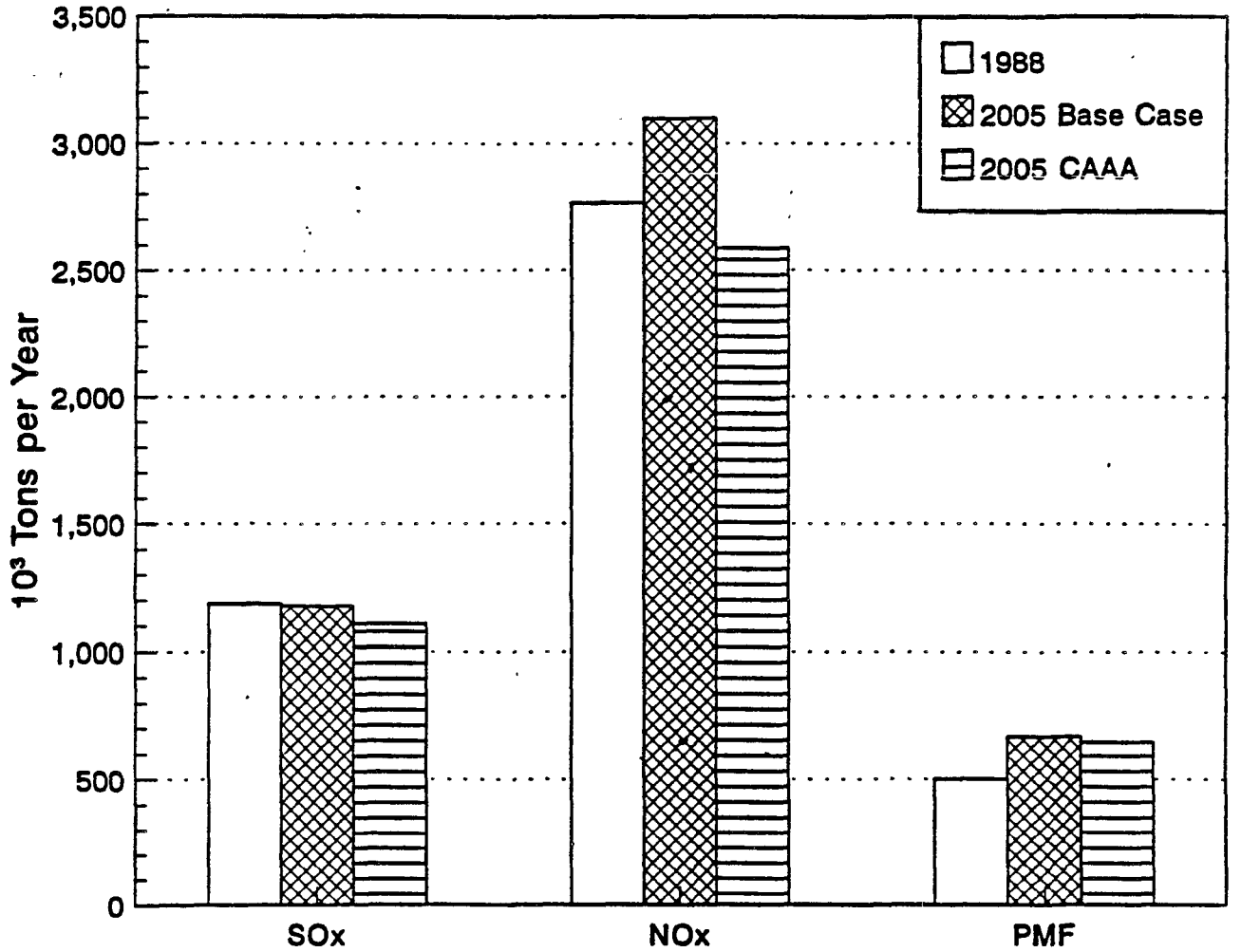


Figure 6-3. Estimated Total Gridded Annual NOx Emissions by Source Category for the Southwestern Analysis (1988, 2005 Base, 2005 Control)

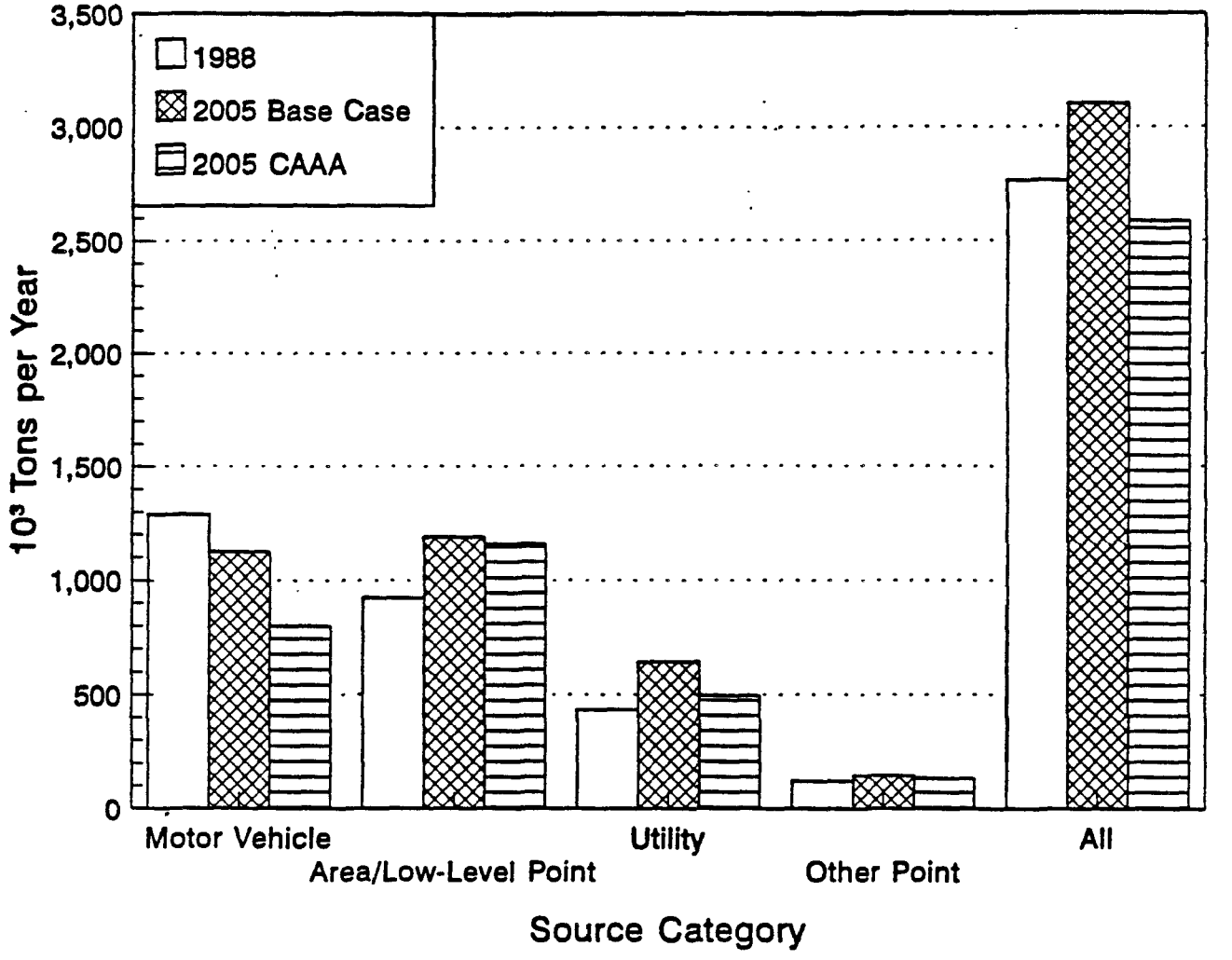


Figure 6-4. Estimated Total Gridded Annual SO2 Emissions by Source Category for the Southwestern Analysis (1988, 2005 Base, 2005 Control)

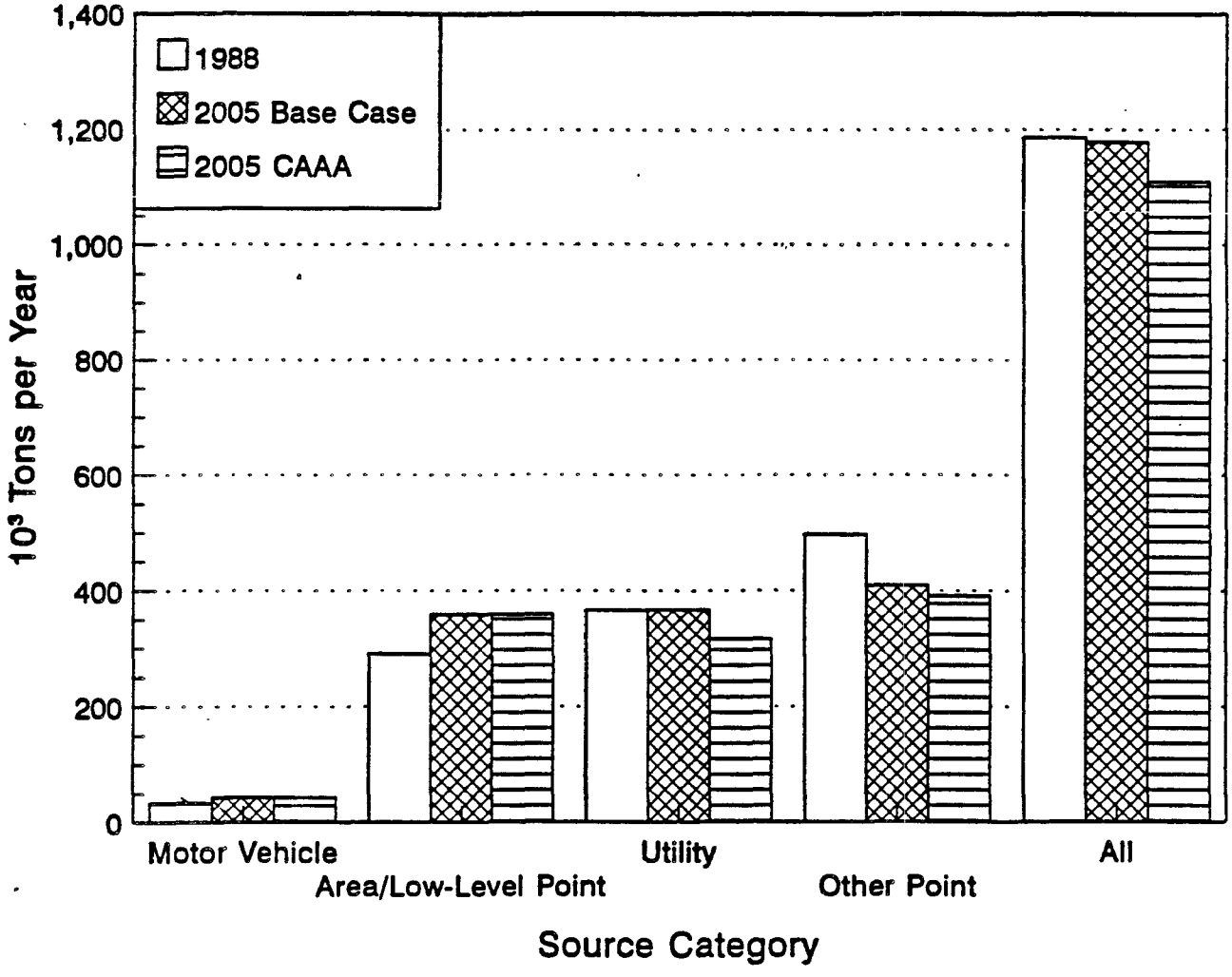
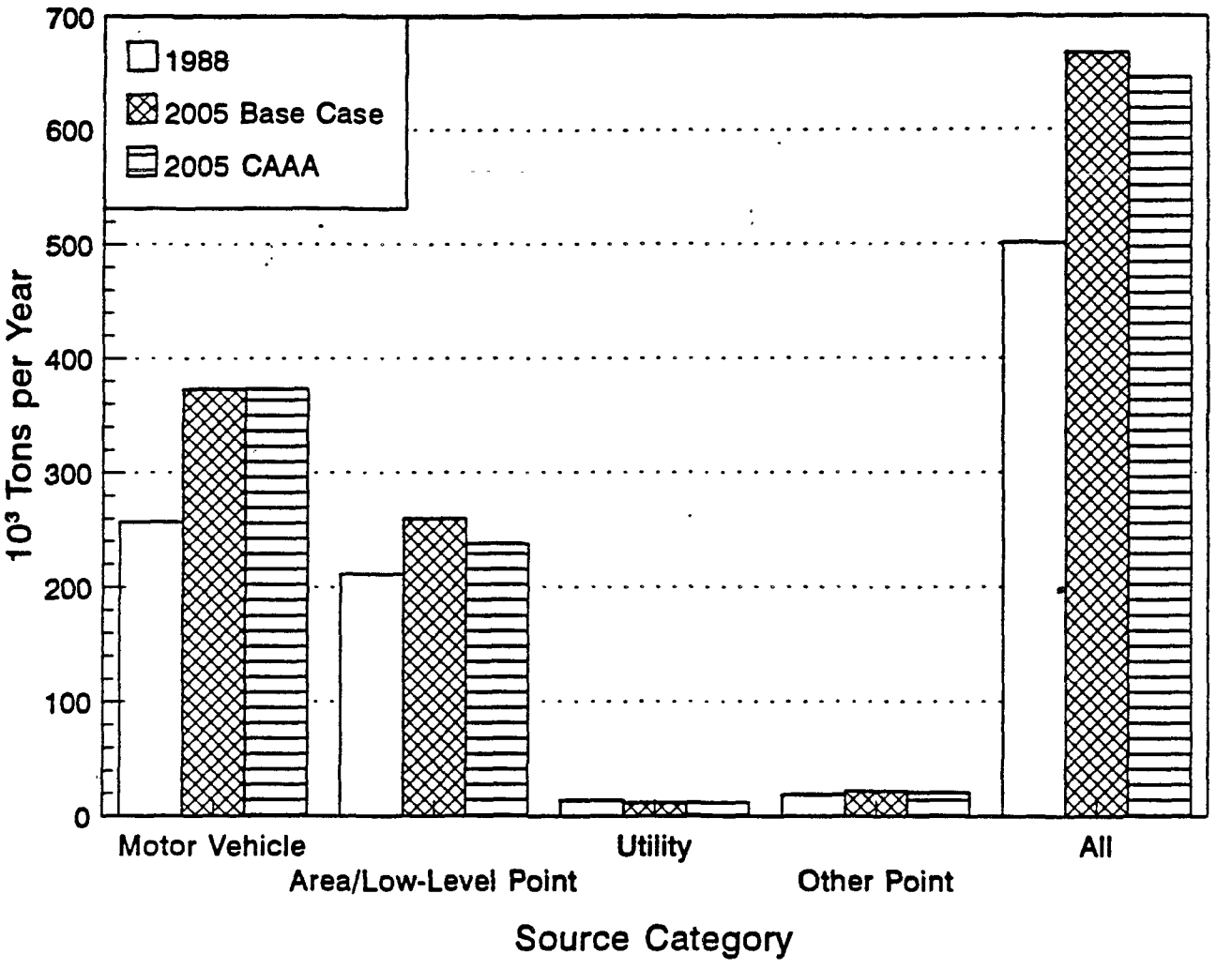


Figure 6-5. Estimated Total Gridded Annual Fine Particle Emissions by Source Category for the Southwestern Analysis (1988, 2005 Base, 2005 Control)



Air Quality Modeling

The emissions inventories prepared for the 1988, 2005 base, and 2005 CAAA control cases were used in an air quality modeling application to estimate the effects of the projected emission changes on long-term regional air quality concentrations in the southwestern U.S. Modeled concentrations of visibility-impairing species were then converted to visibility estimates in each of the class I areas in the modeling domain. To select the most appropriate modeling methodology for this project, several important air quality modeling issues were identified:

> The model must carry the important anthropogenic gaseous and particulate components responsible for visibility impairment, and their precursors;
>
> The model should adequately address the important environmental/meteorological influences on the non-linear chemical interactions between primary precursor species and secondary particulate and gaseous species;
>
> Operating on monthly-seasonal-annual time scales, the model must remain time and cost efficient;
>
> The model should maintain an appropriate level of complexity to adequately represent emission impacts on visibility-related metrics at regional scales (on the order of 100-1000 km).

The use of a computer-based dispersion model was preferred to simulate the physical processes occurring in the atmosphere, including emissions by time and location, their subsequent transport, chemical transformation and deposition. A variety of modeling options, however, were explored for use in this study. The issues listed above were carefully considered for the following modeling options:

> Statistical models (linear chemistry);
> Transfer matrices (linear chemistry);
> Simple grid models (linear or pseudo-first order chemistry);
> Complex grid models (detailed non-linear chemistry).

Statistical models and transfer matrices were determined to be inappropriate because they over-simplify treatment of transport and transformation processes, and because they are most applicable for analyses focusing on particular time scales (rather than a range of time scales). The complexity associated with non-linear grid models prohibited their application to the long integration periods required for this project, particularly for a large regional domain such as the Southwest U.S.

The National Park Service's Air Quality Modeling System (NPSAQMS; Morris and Chang, 1992) was selected for this project. The NPSAQMS contains version II of the Regional Transport Model (RTM-II; a linear chemistry grid model) and a regional version of the SAI Diagnostic Wind Model (METDWM). RTM-II was easily modified to treat all of the major species found to be most abundant in anthropogenic aerosols (PM_{10} and $PM_{2.5}$); its modular structure allowed for the insertion of a pseudo-first order chemical mechanism; and its simplicity allowed integration over long time scales, providing gridded estimates of both short-term (hourly to daily) and long-term (monthly, seasonally, annually) averaged concentrations. The model was found to provide a reasonable characterization of regional-scale transport, transformation, and deposition.

Regional Transport Model

The RTM-II (Morris and Chang, 1992) is a simple three-dimensional Eulerian air quality model that estimates the emission, dispersion, deposition, and chemical transformation of several anthropogenic gaseous and particulate species considered to be most important in visibility degradation and acid deposition. The model originally carried primary anthropogenic emissions of sulfur dioxide (SO_2), sulfate ($SO_4^=$), and nitrogen oxides (NO and NO_2 combined into the single species NO_x), along with secondary linear chemical formation of nitric acid (carried as total nitrate, NO_3^-) and sulfate (combined with primary sulfate). A number of species were added to the model in order to upgrade the sulfate/nitrate chemical mechanism, to allow for the splitting of total nitrate into nitric acid and particulate nitrate, and to account for other primary anthropogenic particulate species; these improvements are discussed in greater detail below. The model now carries primary anthropogenic emissions of SO_2, $SO_4^=$, NO, NO_2, total ammonia (NH_3), fine particulate organic carbon, fine particulate elemental carbon, "other" fine particulate mass (metals, etc.), and coarse particulate mass, along with the original secondary species of total nitrate and sulfate. Modeled species concentrations and deposited mass from all grid cells are output as 3-hour averages for the duration of the model run.

RTM-II Application

An RTM-II modeling domain consisting of a 38 by 26 horizontal grid with 50 km grid cell size was selected for the current study (Figure 6-1). The grid covers most of the significant source areas expected to substantially contribute to visibility degradation in class I areas throughout the southwestern U.S. This rather coarse resolution was not expected to degrade the quality of model predictions when considering the large temporal and spatial scales involved in the analysis.

The three emission scenarios described above were simulated: 1988 base case, 2005 base case (without 1990 CAAA), and 2005 control case (with 1990 CAAA). For each emission scenario, the RTM-II was run for four 30-day periods using meteorological inputs developed for April, July, October, and December 1988. These months were determined to satisfactorily represent each of the four seasons climatologically, except perhaps in terms of rainfall. On one hand, 1988 was one of the worst of the last six drought years in the Southwest, particularly in California. On the other hand, these particular months were selected based on their relative lack of rainfall for two reasons: (1) the mapping of rainfall necessary for 120 days of model application was rather labor intensive; and (2) uncertainties in model results relating to the rainfall analyses and theoretical limitations of the wet deposition routine were minimized.

The RTM-II was configured to estimate the emissions, transformation, dispersion and deposition of anthropogenic aerosol mass, as discussed above, since visibility impacts from future year emissions growth and the 1990 CAAA mandated controls are manifested in changes to only the anthropogenic fraction of particulate mass (and NO_2). Seasonally dependent natural and anthropogenic background components of aerosol mass generated within the domain and entering through the domain boundaries (including sulfate, nitrate, natural/boundary/secondary organic carbon, elemental carbon, and fine and coarse dust) were added to the predicted species for the 1988 base case performance evaluation and for all visibility calculations. Therefore, in the RTM-II model applications, initial and boundary conditions for all aerosol mass were set to zero.

Secondary species such as sulfate, nitric acid, and ammonium nitrate, are formed from both anthropogenic and natural/background precursor gasses. Due to the non-linearity of sulfate and nitrate chemical transformations, it was necessary to include the contributions of background concentrations of NO, NO_2, SO_2, and NH_3 to the formation of the secondary particulate species. In principle, then, modeled "anthropogenic" sulfate and nitrate do include a very small fraction of mass generated from background precursor species. Initial and boundary conditions for the gaseous precursor species were set to global background values (Table 3-2) obtained from previous modeling studies and the literature. The RTM-II was allowed to initialize from the initial state (zero aerosol mass, non-zero gaseous precursor concentrations) over the course of one or two days at the beginning of each month modeled.

Meteorological and Data Input Preparation

The RTM-II requires several environmental input fields to drive the advective, diffusive, chemical, and deposition processes

simulated in the model. Along with two-dimensional static fields containing gridded terrain heights and land use-dependent gridded dry deposition parameters, the model requires time-dependent three-dimensional gridded inputs of wind components, temperature, humidity, pressure, and two dimensional gridded inputs of mixing heights, rainfall rate, and cloud cover. All of the gridded meteorological fields (except rainfall rate) for April, July, October, and December 1988 were prepared using the NPSAQMS METDWM meteorological preprocessor. Data storage considerations and the long-term modeling timescales prompted the development of all time-varying model input data to three-hourly, rather than hourly, formats.

The RTM-II requires gridded ozone concentrations that are used as an estimate of the oxidation potential of the atmosphere for its pseudo-first order chemical mechanism. Observed hourly ozone concentration data for 1988 from the EPA AIRS network were averaged to 3-hourly values then interpolated to each grid cell in the model's mixed layer using an inverse distance weighting within a particular radius of influence (200 km). It was assumed that interpolated surface ozone measurements were representative for the entire mixed depth for a given grid column. For remote areas lacking ozone monitors (i.e. beyond the radius of influence of any monitor) and known to likely experience tropospheric background ozone concentrations (e.g., over ocean, in remote rural areas), ozone concentrations were set to 40 ppb. It was also assumed that ozone at the top of the model (3000 m) was at a tropospheric background value of 40 ppb; ozone concentrations within the upper two layers were linearly interpolated between the mixed layer value and the top of the modeling column.

Reduced ozone input fields were developed for the 2005 control case, following the assumption that full implementation of the 1990 CAAA within all nonattainment areas covered by the modeling domain will be effective in reducing ozone design values to the federal ozone standard. For each 3-hour period, the ozone concentration over a background of 40 ppb, in each grid cell contained within a nonattainment area, was scaled back by the percent difference of the design value for the nonattainment area and the 120 ppb standard.

Air Quality Model Results

After each month was modeled by the RTM-II, season-dependent natural background and anthropogenic boundary contributions were added to the predicted aerosol species at eight representative class I areas containing IMPROVE particulate samplers. These eight sites are Grand Canyon (AZ), Arches (UT), San Gorgonio (CA), Pinnacles (CA), Yosemite (CA), Chiricahua (AZ), Bandelier (NM), and Rocky Mountain (CO). All subsequent performance evaluations and visibility calculations were carried out for these eight class I areas.

Model-predicted 3-hourly concentrations of visibility-related species from the 1988 Base Case scenario were averaged to seasonal values for grid cells covering the eight representative class I areas. Background contributions were then added on a site- and season-specific basis as described above. Resulting concentrations were then compared to 1988 season average IMPROVE data at each site for those species for which direct comparison could be made; these include ammonium sulfate, ammonium nitrate, organics, elemental carbon, total fine mass, and coarse mass.

In terms of absolute differences between modeled and measured concentrations, model performance was quite good at all sites (with minor exceptions); absolute error ranged from 0.0 to about 1.0 $\mu g/m^3$ for most fine mass species. Coarse mass performance tended to be worse in terms of absolute differences, but since the model predicted very little coarse mass for class I areas removed from urban areas, this appeared to be a result of a positive bias between the 1988-1991 average coarse mass used for background conditions and the 1988 average coarse mass. In terms of relative differences, the model performance for most species and most sites ranged from 0% to 50%, averaging 10-20%.

Estimation of Visibility

The air quality modeling results were used to estimate the changes in seasonal and annual average visibility expected in each of eight representative class I areas in the southwestern U.S. due to implementation of the CAAA. First, a light extinction budget was developed for each representative class I area in order to apportion total extinction by atmospheric constituent.

Construction of Extinction Budgets

The 3-hour average concentrations of visibility-related species plus background values at each site were multiplied by their respective extinction efficiencies, and their products were averaged over each season (i.e., modeling month) and for the year. Adding all species extinction coefficients to a Rayleigh scattering coefficient of 10 Mm^{-1} yields seasonal and annual average total light extinction coefficients.

For the 1988 Base case, the relative distribution of extinction agrees rather well with observations and measurements for all sites: extinction in class I areas in the desert Southwest is dominated by sulfate, organics, and dust; extinction at the San Gorgonio site in southern California is dominated by nitrate and organics; while extinction for sites in heavily forested mountainous areas is dominated by organics most likely from biogenic sources.. All sites indicate a large fraction of extinction due to elemental carbon; even at typically low

concentrations below 1 $\mu g/m^3$, the very high extinction efficiency (mostly absorption) causes elemental carbon to contribute substantially to overall light extinction. Overpredictions of ammonium nitrate at Yosemite and Rocky Mountain are manifested in high nitrate contributions to overall extinction at those sites.

Visual Range and Deciview Estimates

Visual range and deciview were calculated from the 3-hour average extinction budgets and averaged to seasonal and annual average values. Figures 6-6 through 6-13 display visual range and deciview at all eight class I areas by season (and annual average) for all three emission scenarios. The growth in emissions between 1988 and 2005 base cases is reflected in a slight reduction of visual range predicted at all sites during the entire year. Controls required by the CAAA are predicted to offset this emissions growth so that visual ranges for the CAAA control case are predicted to be similar to 1988 base case levels. Changes are quite small (less than one DV) in all cases except San Gorgonio. In the case of San Gorgonio wilderness a special review of the influence of nitrate on the extinction budget and the resulting change in nitrate concentrations that might occur with attainment of the ozone ambient standard in the Los Angeles area, indicates that this area could see perceptible improvements in visibility of 1-2 deciviews due almost entirely to reductions in aerosol nitrate.

Southwestern Modeling Conclusions

The RTM-II dispersion model was used to estimate the expected changes in air quality and visibility at class I areas in the southwestern U.S. due to implementation of the 1990 CAAA. Provisions of the CAAA were examined to determine the effects on future emissions and then these emission projections were used in the model to develop estimates of changes in ambient concentration of visibility-related species. The effect on extinction budgets, visual range and deciview were then estimated from the change in concentrations.

Significant emission reductions mandated by the CAAA are targeted primarily at nonattainment areas. However, those provisions of the CAAA, for which quantifiable emission reductions could be determined, were estimated to result in only modest emission reductions throughout the southwest modeling domain. Not surprisingly, therefore, modeling results indicate that little change is to be expected in the distribution of visual range at class I areas. For example, implementation of the CAAA by 2005 is estimated to increase visual range at Grand Canyon National Park from 122.5 km to 123.2 km, an increase of only 0.6 percent.

Figure 6-6. Estimated Visibility (visual range and deciview) at Grand Canyon National Park

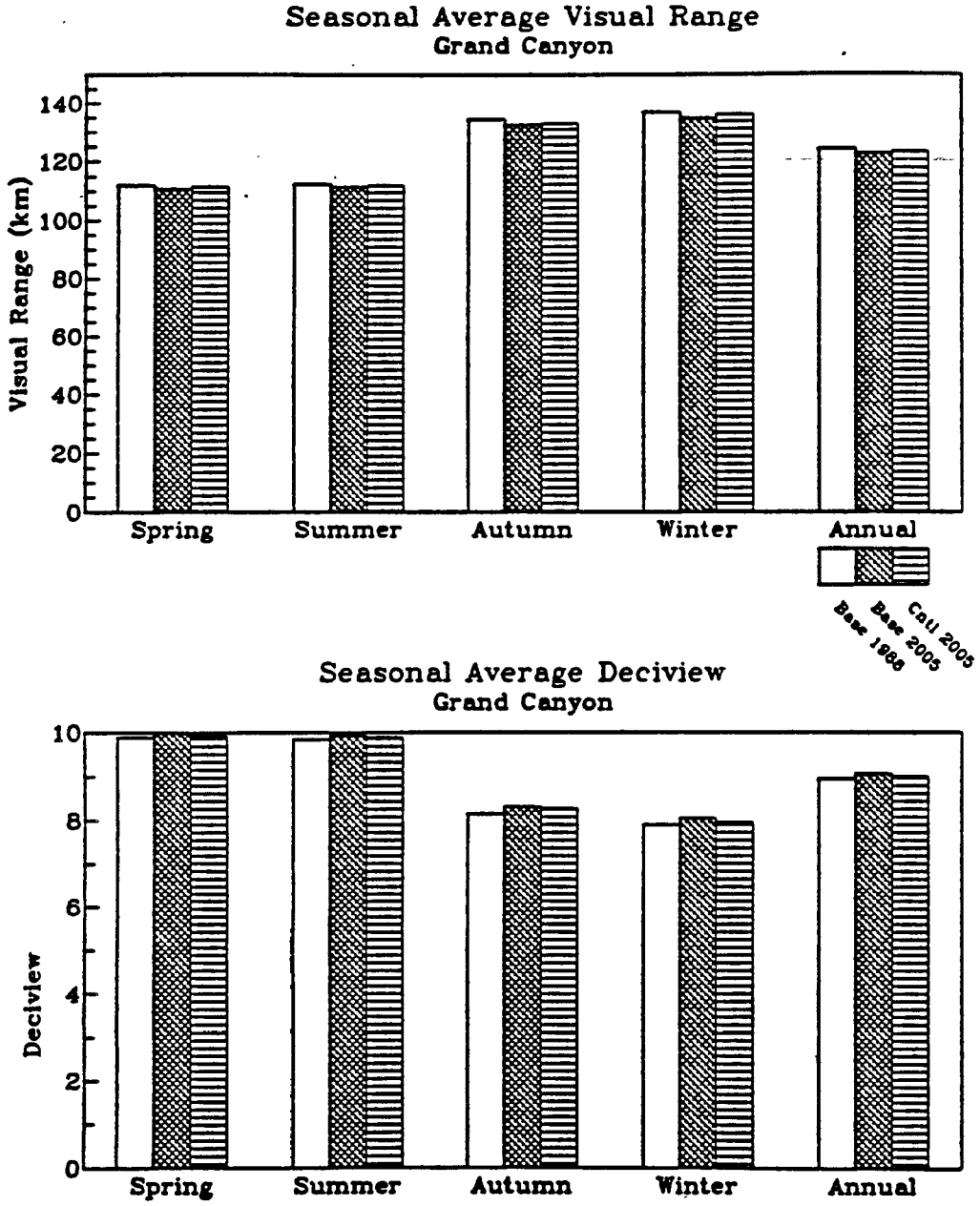


Figure 6-7. Estimated Visibility (visual range and deciview) at Arches National Park

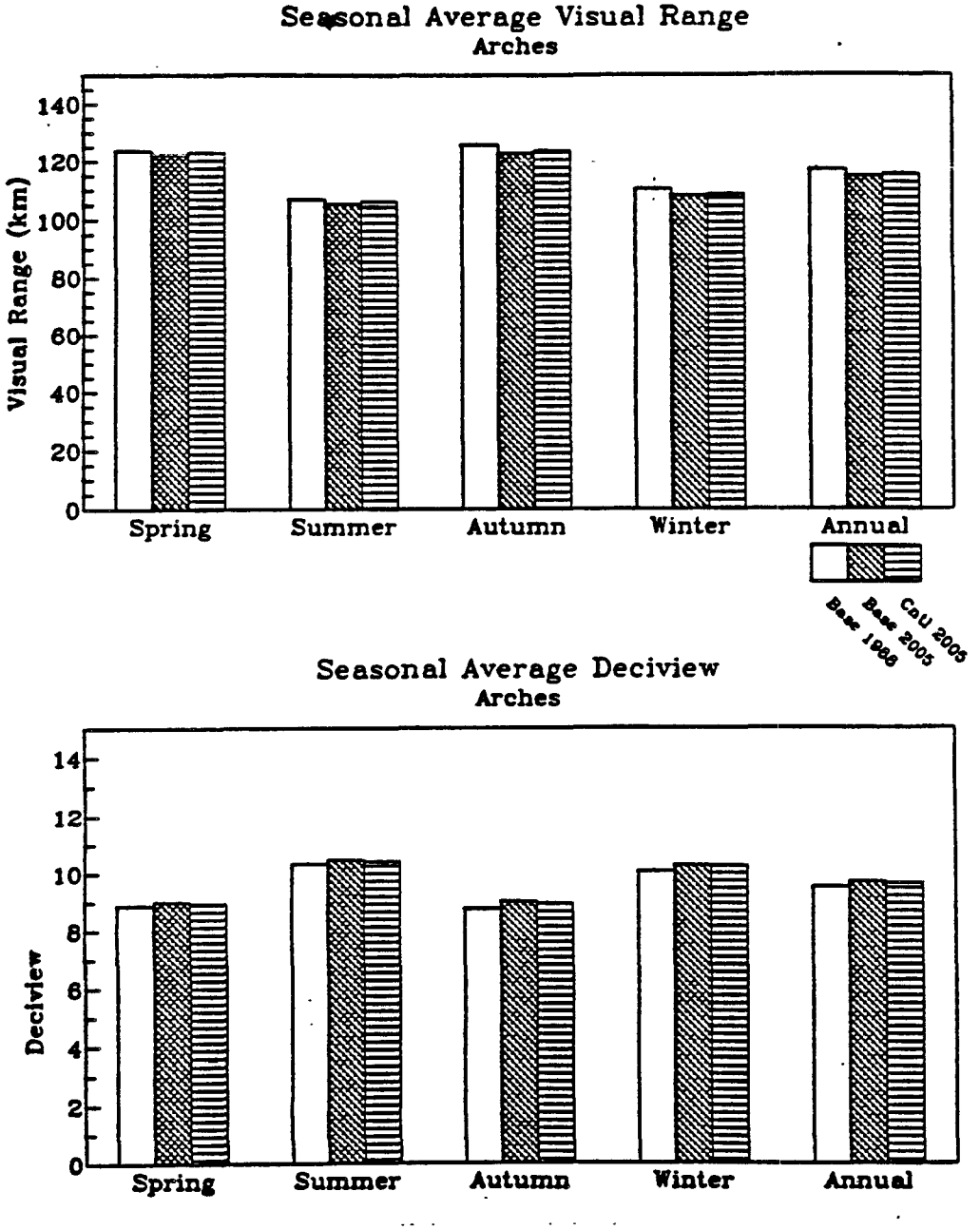


Figure 6-8. Estimated Visibility (visual range and deciview) at San Gorgonio Wilderness

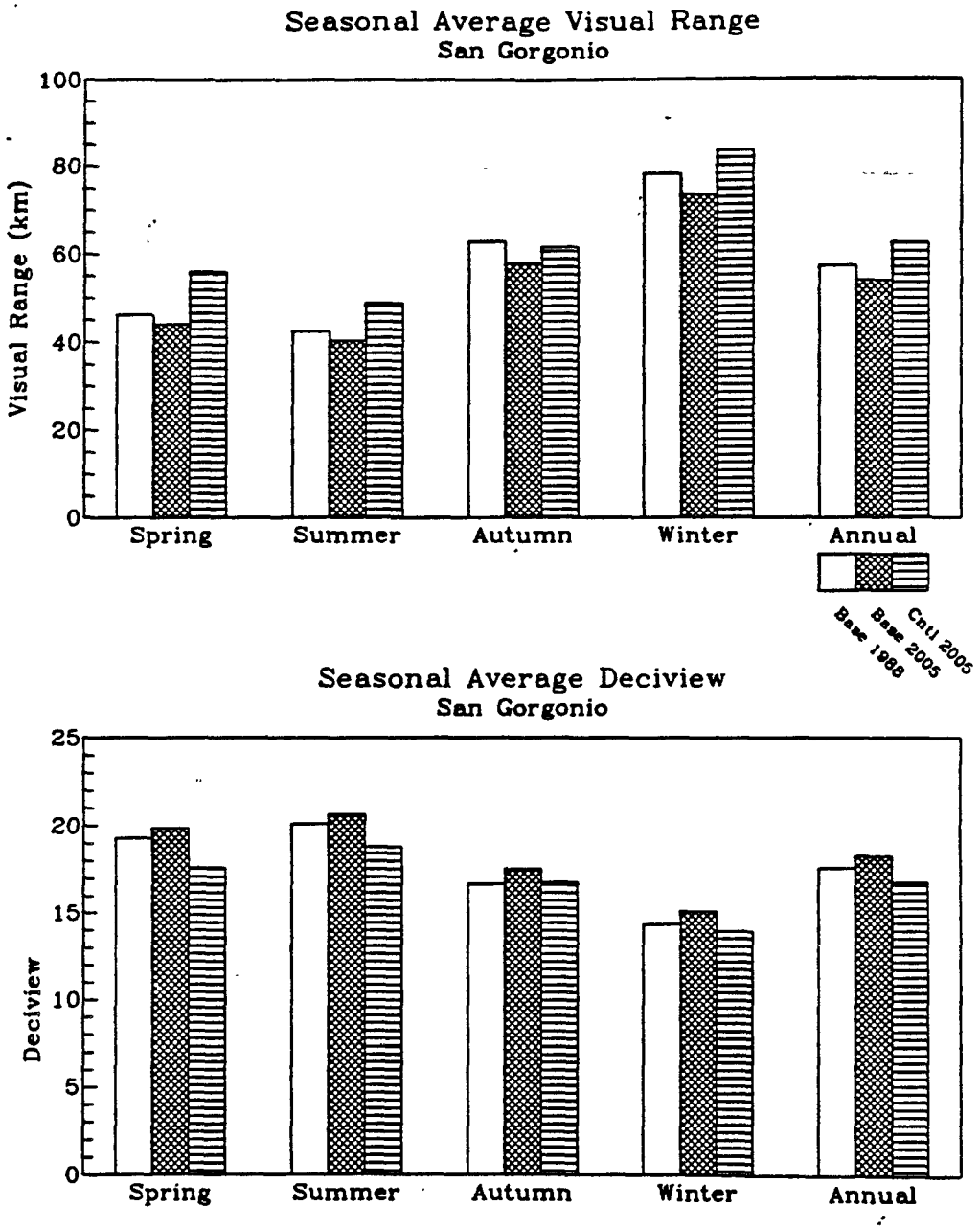


Figure 6-9. Estimated Visibility (visual range and deciview) at Rocky Mountain National Park

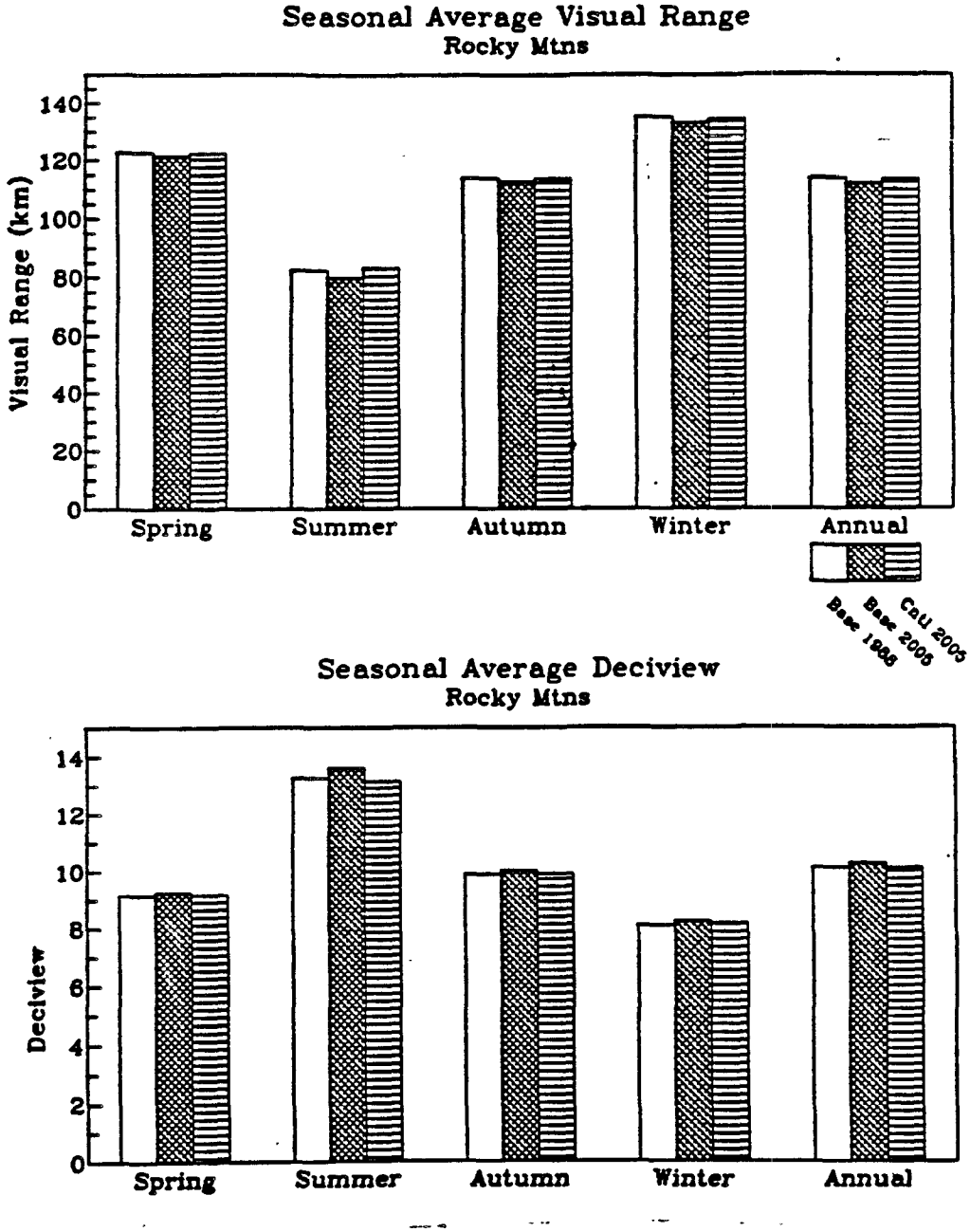


Figure 6-10. Estimated Visibility (visual range and deciview) at Pinnacles Wilderness

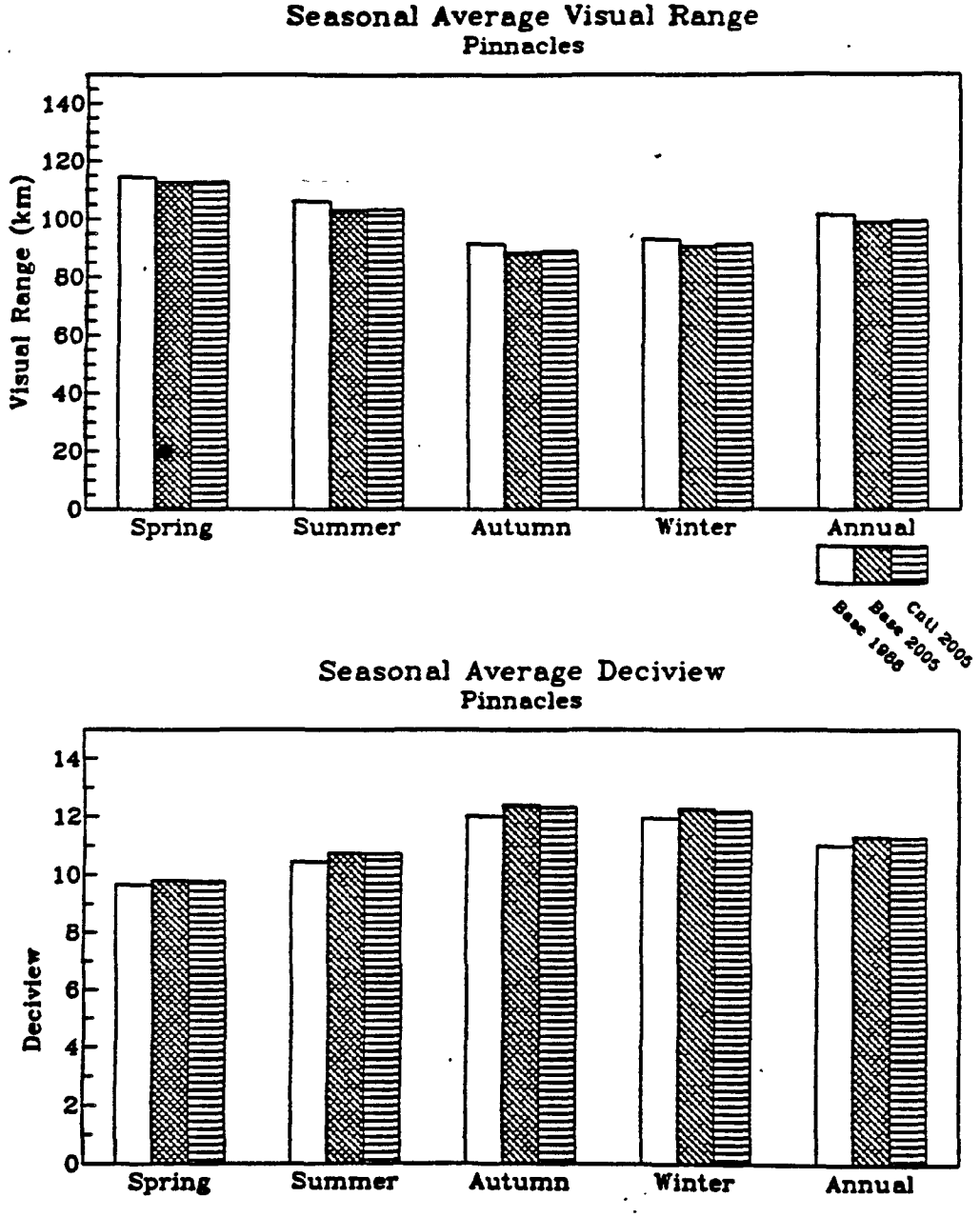


Figure 6-11. Estimated Visibility (visual range and deciview) at Yosemite National Park

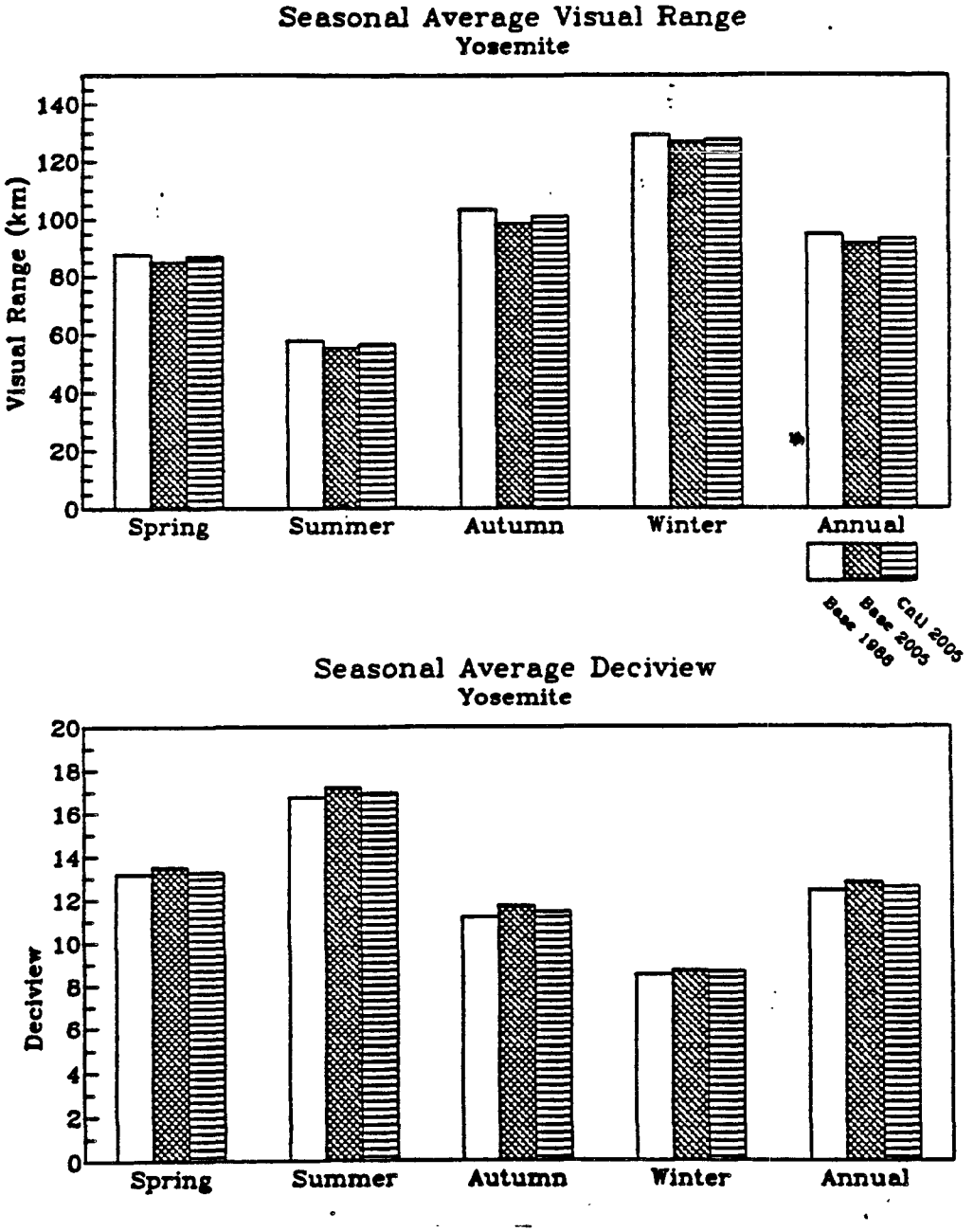


Figure 6-12. Estimated Visibility (visual range and deciview) at Chiricahua Wilderness

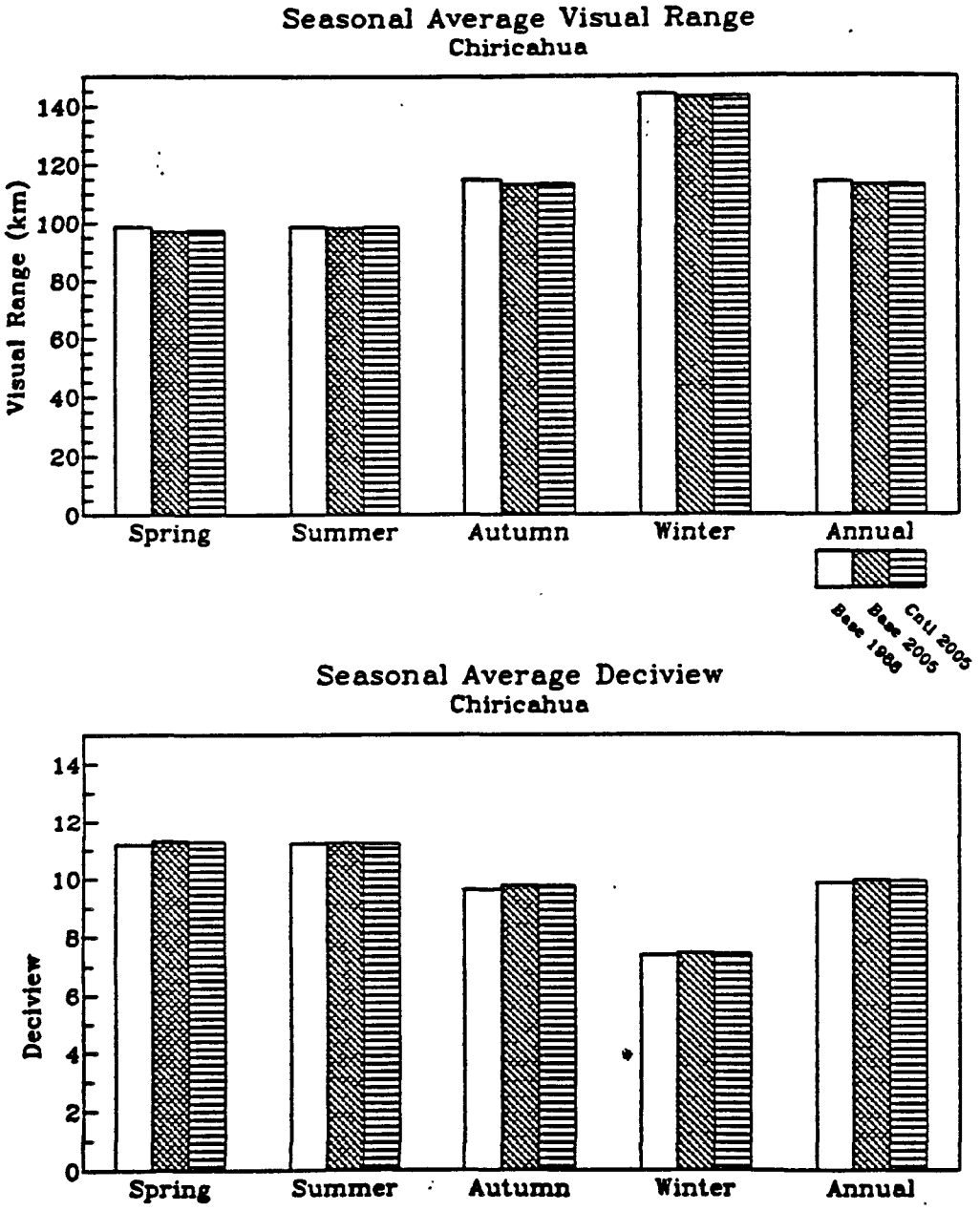
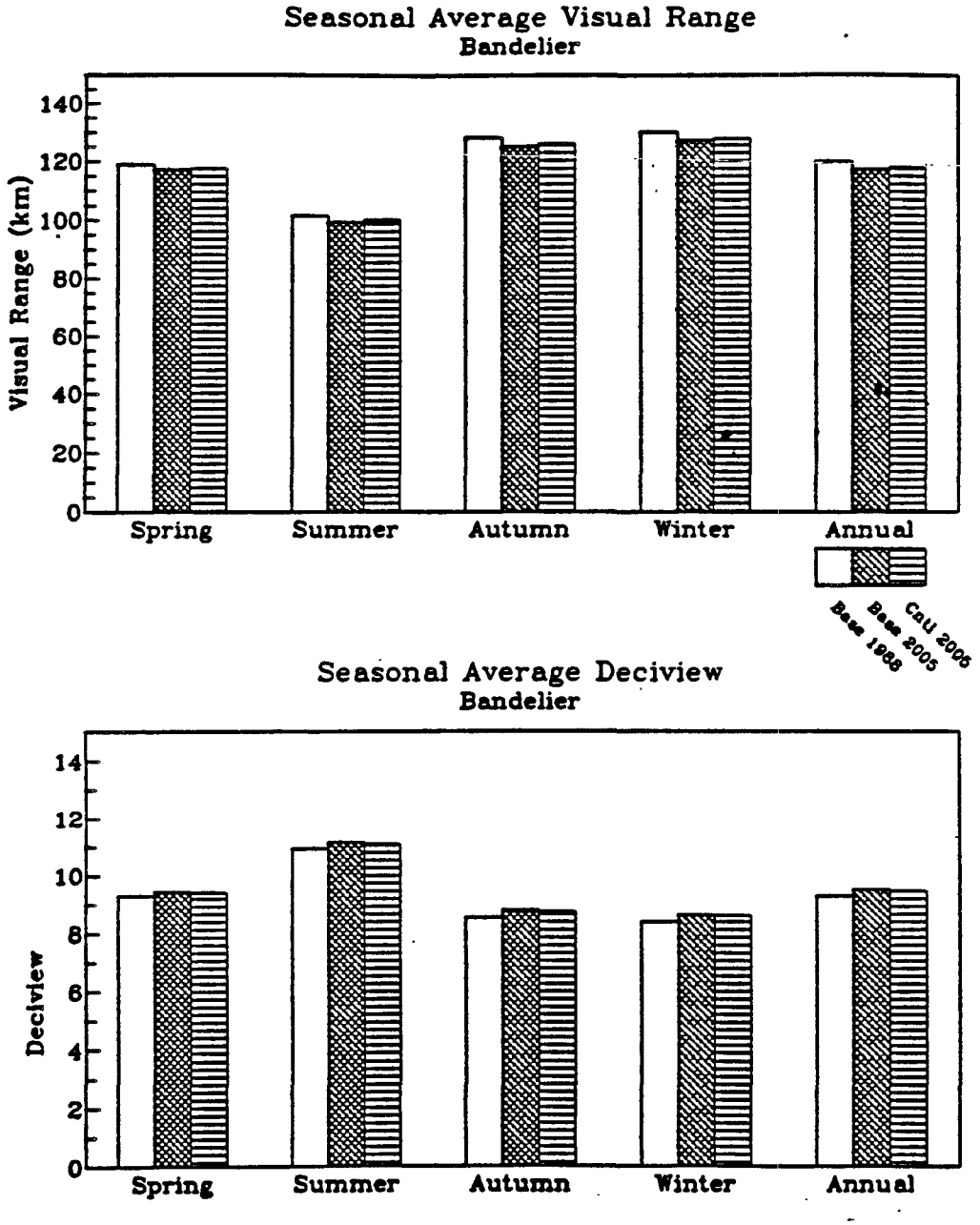


Figure 6-13. Estimated Visibility (visual range and deciview) at Bandelier Wilderness



This shift in the distribution of visibility conditions is not significant. The only exception to this limited change was the review of nitrate changes at San Gorgonio wilderness showing a 1-2 deciview improvement in annual average visibility levels. However, the predicted 1-2 deciview improvement is dependent on the Los Angeles area meeting attainment of the ozone national ambient air quality standard by 2005.

Uncertainties

Emissions

The results presented in this report are based on a number of assumptions. The air quality modeling results, and hence the estimates of future visibility, are sensitive to a number of inputs, some of which are fairly uncertain. For example, emission projections indicated that, without the CAAA, there would be sufficient growth in emissions generating activities between 1988 and 2005 to largely offset the expected NO_x emission reductions and more than offset the modest reductions expected in fine particle emissions. A significant amount of growth in particulate emissions was due to predicted growth in mobile source VMT estimates which are fairly uncertain. If actual VMT growth was less than estimated, larger improvements in visibility would have been demonstrated. However, the predicted visibility difference between the two future year scenarios (with and without CAAA) would not be significantly changed.

As in any study of this type, uncertainties in emissions are likely to be large. The VOC emissions were not examined due to their relatively small role in visibility in the remote Southwest and the high cost of including them in the study. It should be noted that the 2005 base case is a highly artificial case, but it is useful as a reference case for assessing the magnitude of effects from uncontrolled growth in emission-generating activities. The emission increases due to increases in VMT are particularly striking. It should also be noted that the 2005 CAAA case includes only quantifiable emission reductions directly required by the 1990 CAAA. The effects of other CAAA provisions and state and local programs are not included, so actual 2005 emissions may possibly be lower than assumed in this study, resulting in improvements in visibility not estimated here.

Role of Secondary Organic Aerosols

Secondary organic aerosols (SOA) arise from the photochemical oxidation of certain VOC emissions, which produce low vapor pressure products that can condense into the aerosol phase. SOA can form from either anthropogenic or biogenic VOC emissions; in fact, the aerosol-forming potential of biogenic VOC is much greater than that of most anthropogenic VOC (e.g., Grosjean and

Seinfeld, 1989). Estimates of the secondary contribution to organic aerosol concentrations have been made for the Los Angeles area (Gray et al., 1986; Turpin and Huntzicker, 1991; Pandis et al., 1992), and tend to be in the range of 20 to 40 percent during the summer. In the winter, little SOA would be expected because of reduced photochemical activity. Since organic aerosols often account for 30 to 50 percent of fine mass, secondary organic aerosols potentially contribute up to 20 percent of fine mass during the summer, a fraction comparable to the sulfate contribution in many locations and greater than the nitrate contribution in all but the most polluted locations.

Methods for identifying the secondary component of organic aerosols often focus on the ratio of organic to elemental carbon (OC/EC). If OC/EC for the primary aerosol is known, then SOA can be identified by increases in OC/EC. The difficulty with this approach is that primary OC/EC is not constant for all source types. If variations in primary OC/EC are large, then uncertainties in estimating the SOA will also be large.

The RTM-II does not currently include SOA formation, as discussed above. Thus, the estimates derived in the present study of the impact of the CAAA on fine particle concentrations and visibility do not include any possible reductions in SOA that might arise from the CAAA. Yet, reductions in precursor VOCs are required by the CAAA in ozone nonattainment areas, and could potentially impact SOA concentrations in downwind class I areas.

To estimate the contribution of SOA at class I sites, and the potential reductions in SOA due to the CAAA, the OC and EC data from selected IMPROVE sites within the modeling domain were examined. In the Los Angeles studies, ambient OC/EC ratios were available either with high temporal resolution (Turpin and Huntzicker, 1991), or for several sites at various downwind distances from the primary source region (Gray et al., 1986). In both cases, primary OC/EC ratios could be estimated readily, either from the early morning ambient OC/EC ratio or from the ambient OC/EC ratio in near-source regions. However, neither of these approaches could be used with the IMPROVE data. Instead, winter minimum OC/EC ratios were used as a surrogate for the primary OC/EC ratios, and the SOA contribution in summer was estimated from the differences between the summer and winter OC/EC.

Table 6-4 shows the measured winter minimum OC/EC and the summer mean OC/EC for selected IMPROVE sites. For each site, the winter minimum was calculated based on an average of the lowest 6 to 10 values. The estimated summertime contribution of SOA ranges from 13 to 55 percent, amounting to 0.5 to 1.2 $\mu g/m^3$. The maximum estimated SOA concentration occurs at San Gorgonio, located downwind of the Los Angeles area.

Table 6-4. Summer and Winter OC/EC Data and Estimated Summer SOA Concentrations at Selected IMPROVE Sites.

SITE	Winter minimum OC/EC	Summer mean OC/EC	Summer SOA percent	Summer OC ($\mu g/m^3$)	Summer SOA ($\mu g/m^3$)
Grand Canyon	2.02	4.60	56	1.26	0.71
Arches	2.80	5.99	53	1.40	0.74
Pinnacles	2.42	4.38	45	1.15	0.52
Bandelier	3.09	6.41	52	1.18	0.61
Rocky Mtn	2.90	5.94	51	2.20	1.12
Yosemite	3.65	4.18	13	4.13	0.54
San Gorgonio	2.13	3.37	37	3.22	1.19
Chiricahua	2.82	6.29	55	1.35	0.74

The uncertainties in these values are high, mainly because of the uncertainty in the validity of the assumption that the OC/EC ratio is constant for summer and winter. There are numerous reasons why this may not be the case. Wood burning emissions, for example, are characterized by very high OC/EC ratios and have strong seasonal patterns. Areas impacted by residential wood combustion in winter, or forest fires, prescribed burns, or even campfires in summer, may exhibit high OC/EC ratios that are not due to secondary formation. In addition, primary biogenic organic aerosols may have a significant impact upon total organic aerosol concentrations in class I areas (Simoneit and Mazurek, 1982).

To estimate an upper bound to the possible reduction in SOA due to the CAAA, the San Gorgonio site was used for further analysis. First, the estimate of Pandis et al. (1992) of 0.5 $\mu g/m^3$ for biogenic SOA at Claremont was assumed to represent a lower bound for the biogenic SOA concentration at San Gorgonio (San Gorgonio is much more heavily wooded than the Los Angeles basin). The contribution of primary biogenic organic aerosol was 0.2 $\mu g/m^3$ (Simoneit and Mazurek, 1982). Of the 1.2 estimated at estimated for total SOA concentration in summer, subtraction of 0.7 $\mu g/m^3$ due to biogenic primary and secondary organic aerosol leaves an estimated anthropogenic SOA concentration of 0.5 $\mu g/m^3$.

In order to meet the CAAA deadline for ozone attainment, the Air Quality Management Plan for the Los Angeles area calls for VOC reductions of 83 percent (SCAQMD, 1991). Therefore, the reduction in anthropogenic SOA at San Gorgonio due to the CAAA is estimated at 83 percent of 0.5 $\mu g/m^3$, or 0.42 $\mu g/m^3$. Applying the scattering efficiency for organic aerosol of 6 m^2/g gives an estimated reduction in summertime extinction of 2.5 Mm^{-1} for SOA. Although this is a significant fraction of the extinction reduction for San Gorgonio simulated by the RTM-II, it is still small in an absolute sense. Keeping in mind that this estimate has a high degree of uncertainty, it suggests that future modeling analyses of visibility impacts in Southern California should address SOA.

The impact of the CAAA on total extinction at all other class I areas will be considerably smaller than the estimate derived for San Gorgonio, for two reasons. First, the estimated total SOA concentration (including primary biogenic organic aerosol) in Table 6-4 is lower at all other sites, ranging from 0.5 to 1.1 $\mu g/m^3$. Assuming a minimum total biogenic contribution of 0.7 $\mu g/m^3$ leaves only Rocky Mountain National Park with any significant estimated anthropogenic SOA contribution. Second, the VOC reductions required by the CAAA will be lower for air basins located upwind of all other sites than the 83 percent assumed for the Los Angeles area.

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Chapter 7. Comparison of Modeling Approaches

Comparison of Eastern and Southwestern Approaches

Estimates of Current and Future Emissions

Independent procedures for estimating base case and future year emission levels under the provisions of the 1990 CAAA were used for the eastern and southwestern U.S. visibility modeling studies. Differences in the projection procedures arise primarily as a result of the different requirements of the eastern and southwestern visibility modeling approaches: emission estimates for the Southwest were prepared for SO_2, NO_x, and particulate matter for 1988 (base case) and 2005 (base and control cases), while emission estimates for the East were prepared for SO_2 only for 1985 (base case) and 2010 (control case). In both areas, future year SO_2 emission reductions were assumed to result solely from changes in emissions by electric utilities in response to changes in electric power demand and full implementation of the provisions of Title IV of the 1990 CAAA.

In the southwestern analysis, future year utility SO_2 emissions were estimated using the Coal Electric Utility Model (CEUM) as described in the SO_2 regulatory impact analysis (RIA) prepared by ICF Resources. This model accounts for the SO_2 emission allowance trading and banking provisions of Title IV. The CEUM results were based on the demand forecast and fuel price assumptions contained in the "RIA low trading case" used in the SO_2 RIA. Since these assumptions are currently considered outdated, modifications were made to the CEUM results to bring the power production and fuel use predictions in line with current government and industry forecasts for the Southwest. These modifications resulted in virtually no increase in coal consumption, and very little increase in oil consumption between 1988 and the 2005 control case.

In the eastern analysis, projected utility SO_2 emissions were estimated based on DOE forecasts of electricity demand ("Annual Outlook for U.S. Electric Power 1991", DOE/EIA(91), July, 1991). These estimates were used in conjunction with assumptions about unit retirement rates, capacity utilization, etc. contained in the "EPA High Base Case" as input to the AIRCOST/PC model to allocate generation by existing, planned, and (new) unplanned units and thus obtain projected SO_2 emissions for 2010. This approach did not account for any effects of trading or banking of SO_2 emission allowances on the total amount and geographical distribution of SO_2 emissions. However, the effect of allowance banking over the time period of interest (to the year 2010) is likely to be negligible and any geographic shifts in emissions within the East due to large scale allowance trading are

speculative and not likely to effect the conclusions regarding visibility improvements for the region as a whole.

Although the procedures used to estimate reductions in SO_2 emissions resulting from implementation of the 1990 CAAA were different in the Southwest and the East, both approaches are believed to provide reasonable estimates of future year SO_2 emissions under the 1990 CAAA.

Comparison between RTM-II and RADM Visibility Modeling

Several significant differences exist between the air quality/visibility modeling efforts carried out for the eastern U.S. (using RADM-EM) and the southwestern U.S. (using RTM-II). First and foremost, these two air quality models differ in the chemical species they carry, and in their treatments of the physical processes responsible for dispersion, deposition, and chemical transformation. Although RADM-EM is a simplified version of RADM2.0, it incorporates many more physical processes, and more complex parameterizations, than those included in the RTM-II. Second, the methods used to calculate visibility estimates from model output concentrations differ substantially between the two regions. While the methods employed for the southwest are rather complete and detailed, the analysis for the east is primarily based on sulfate concentrations, modified to include contributions of non-sulfur species to total light extinction.

The full RADM 2.0 modeling system incorporates a 3-D Eulerian framework, in which 6 layers of 35x38 80 km grid cells are specified to cover the eastern U.S. from the surface up to about 15 km. This results in resolving the lowest 3000 m of atmosphere into 4 vertical layers. The model is based on solving a conservation equation that treats emissions, dispersion, deposition, and chemical transformation of 63 chemical species within each model cell. RADM employs the Smolarkewicz advection scheme, along with explicit first-order vertical diffusion based on bulk parameterizations of turbulent exchange coefficients in various atmospheric layers. The model is supplied with emissions of SO_2, SO_4, NO, NO_2, 16 species of VOC, NH_3, and CO. The gas-phase chemical mechanism is a highly detailed non-linear mechanism that simultaneously solves 157 chemical reactions that include 42 species of organics and 20 photolysis rates. Dry deposition is calculated based on the resistance method in three physical regimes: the turbulent boundary layer, the laminar sublayer, and the canopy layer. RADM requires the specification of cloud fields (including location, type and coverage) to calculate aqueous chemical transformations, wet removal, and the vertical redistribution of pollutants in convective-type cloud systems.

The RADM-EM was designed to reduce the excessive computational cost of running RADM2.0. It is internally identical to RADM in all respects except that the chemical transformation mechanisms are a mathematical approximation of the chemical parameterizations in the full non-linear model. RADM-EM directly treats only those gas- and aqueous-phase reactions related to sulfur, and therefore only predicts the emissions, dispersion, transformation, and deposition of SO_2, SO_4, and H_2O_2. Photolysis and aqueous chemical rates are calculated in a manner identical to that of the full RADM model, but OH and HO_2 concentrations are externally supplied from the RADM output chemical files. This procedure is based on the inherent assumption that NO_x/VOC chemistry remains unchanged for a particular set of RADM-EM simulations; therefore, RADM-EM can handle input emissions inventories in which only sulfur loadings are altered. The model requires RADM input meteorological files and RADM output chemical files, and recomputes sulfur air quality using various sulfur emission inventories.

Whereas RADM-EM explicitly treats the production of sulfate via both gaseous and aqueous pathways, and parameterizes dry and wet surface removal (all using highly complex and non-linear methods), sulfate is the only aerosol species carried by the model. On the other hand, RTM-II condenses gaseous sulfur and nitrogen oxidation into pseudo-first order calculations while parameterizing humidity-dependent oxidation rates and dry surface deposition rates in a rather simplistic manner. However, RTM-II carries several species (nitrate, primary organics, etc.) known to play crucial roles in visual air quality throughout the western U.S. Besides the chemical aspects, RTM-II also departs from RADM-EM in its treatment of vertical grid structure in that the first layer of RTM-II contains the entire mixing layer, while two upper layers evenly divide the region between the top of the mixed layer and the top of the model at 3000 m. Many other aspects of RTM-II, however, are similar to RADM-EM, including wet deposition and Smolarkewicz advection algorithms. Calculated dry deposition rates, although simplistic compared to RADM, utilize RADM land use categories and first-order reaction rates based on RADM calculations. The 3-D Eulerian RTM-II was configured for the southwest using 3 layers of 38x26 50 km grid cells.

As a result of the simplifications required in modeling sulfur controls with RADM-EM, the calculation of visibility-related parameters in the eastern U.S. was limited to light extinction from natural temperature- and pressure-dependent Rayleigh scattering and aerosol scattering due to sulfate. Sulfate scattering efficiencies were determined using a formulation in which efficiencies increase logarithmically with relative humidity. Gridded total base case extinction (Rayleigh plus sulfate) was uniformly scaled up so that total extinction averaged over the entire RADM domain equaled the domain-average

observed extinction from eastern U.S. IMPROVE sites. This was done to incorporate the contributions of other non-controlled aerosol species to total extinction. This same extinction increment was used for the sulfur control results (again, impacts to extinction resulted from changes to sulfate air quality only). Seasonal and annual distributions of visual range and deciview were then calculated from the gridded extinction data for each emissions scenario.

For the southwest U.S., visibility-related parameters were calculated using RTM-II concentrations augmented with specified background concentrations based on measurements at several western IMPROVE sites. Light extinction was calculated using a widely accepted constant value for Rayleigh scattering, and impacts from the following constituents: NO_2; modeled and natural background sulfate; modeled and natural background aerosol nitrate; modeled primary, natural, and anthropogenic secondary organics; modeled and natural elemental carbon; modeled "other" fine mass (metals, road dust, etc.) and natural fine dust; and modeled coarse mass and natural coarse dust. Extinction efficiencies for sulfate, nitrate, and organics were calculated from humidity-dependent logarithmic functions similar to that used for sulfate in the eastern U.S. Extinction efficiencies for the other species were held constant at widely accepted values. In the South Coast Air Basin, extinction efficiency for organics was held constant, assuming that organics in that area do not tend to be as hygroscopic due to their differing origin and formation pathways. Seasonal and annual distributions of deciview and visual range were then calculated from gridded extinction data for each emissions scenario.

In summary, RADM-EM models only sulfur species, but the model contains superior mechanisms over RTM-II for gaseous and aqueous sulfur oxidation pathways, and for dry and wet deposition calculations. This is important for estimating baseline and future visibility-related parameters in the eastern U.S. since sulfate dominates visual air quality in that region. RTM-II, on the other hand, simplifies treatments of sulfur oxidation chemistry and deposition, yet models several other significant primary and secondary aerosol species. The design of RTM-II makes it more applicable to modeling visual air quality in the western U.S.; in comparison to the east, the smaller and more wide-spread sulfur emission loadings, combined with the drier environment, lead to less sulfate formation. This results in a larger fraction of several other aerosol chemical species such as nitrate, organics, and dust, most of which are in turn influenced by 1990 CAAA controls.

Sensitivity of Results

As mentioned in the discussion of the modeling approaches, the emissions growth factors for general economic development are key to regional changes in visibility beyond the major sulfur dioxide reductions expected under Title IV of the Clean Air Act as amended. If economic growth is slower than projected or if new industrial processes are developed that produce less pollution for the same industrial output, then more improvements in regional visibility could occur than those predicted in this report. This may be the case for class I areas near the Los Angeles Basin which are close to showing perceptible improvement in this review.